GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

AUTOMATED MEMBRANE CASTING APPARATUS FOR NOVEL ENERGY STORAGE ARCHITECTURES

Autor: Ángel Sánchez-Cantalejo Hevia

Director: Enrique S. Gutiérrez-Wing

Madrid

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Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título
Automated Membrane Casting Apparatus for Novel Energy Storage Architectures
en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el
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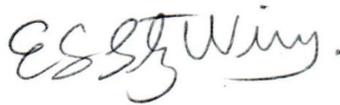Fdo.: **Ángel Sánchez-Cantalejo Hevia**   Fecha: **13 / 07 / 2022**

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EL DIRECTOR DEL PROYECTO

Fdo.: **Dr. Enrique S. Gutiérrez Wing**   Fecha: **06/JUL/2022**

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APARATO AUTOMATIZADO DE MOLDEO DE MEMBRANAS PARA NUEVAS ARQUITECTURAS DE ALMACENAMIENTO DE ENERGÍA

Autor: Sánchez-Cantalejo Hevia, Ángel.
Director: Gutiérrez-Wing, Enrique S..
Entidad Colaboradora: Boston University – Laboratorio de Materiales y Dispositivos Mesostructurados (MeMaD).

RESUMEN DEL PROYECTO

Palabras clave: Moldeo de Películas, Electrodos de Batería, Consistencia, Cuchilla de Moldeo, Investigación en Baterías, Grosor, Automatizado,

1. Introducción

El profesor Jörg Werner, doctor de la Universidad de Boston, es el principal cliente de este proyecto junto con su colaborador Anton Resing (estudiante de posgrado). La investigación del profesor Werner se centra en los materiales y dispositivos funcionales con estructuras de nano a microescala que se consiguen mediante el autoensamblaje molecular, la separación de fases y otros métodos. Dirige el laboratorio de Materiales y Dispositivos Mesoestructurados (MeMaD) donde, junto con su colaborador Anton Resing, investiga el uso de electrodos de baterías como método de transporte de iones.

En septiembre de 2021, el profesor Werner necesitaba un dispositivo que pudiera utilizarse para fabricar electrodos de batería estructurados jerárquicamente, que resultan de un proceso de separación de fases que se produce cuando una solución polimérica moldeada se sumerge en un baño de precipitado disolvente como, por ejemplo en este caso, de agua. Este proceso puede realizarse a mano, pero para lograr la reproducibilidad necesaria para los estudios sistemáticos, se necesitaba un aparato automatizado de moldeo de películas con varios parámetros de control. La implementación exitosa de este dispositivo daría como resultado electrodos de batería que podrían servir como base arquitectónica para baterías estructuradas tridimensionalmente que tienen el potencial de disminuir drásticamente el tiempo de carga de la electrónica de dispositivos personales, permitir el almacenamiento eficiente de energía sobre chip y desempeñar un papel influyente en la mejora de la durabilidad de las baterías. Una vez implementado el aparato, se

quedaría con los clientes del laboratorio MeMaD para ser utilizado como material clave de su posterior investigación.

La razón por la que se ha indicado anteriormente para qué necesita este dispositivo el profesor Werner es para introducir la motivación que ha seguido al proyecto. Sin embargo, es importante resaltar que este proyecto no se ha centrado en la investigación de los electrodos de la batería que servirán como método de transporte de iones, sino en el diseño y construcción del aparato que proporcionará la consistencia necesaria para poder llegar a resultados concluyentes en dicha investigación.

El problema al que se enfrentaba el laboratorio del profesor Werner es que las membranas de inversión de fase están sujetas a variaciones debido a inconsistencias en el moldeo de las películas poliméricas. En septiembre, no había ningún proceso automatizado para el moldeo de estas membranas en su laboratorio y por eso se hacía de manera manual. Esto daba lugar a dos tipos de inconsistencias: <u>dentro de una misma membrana</u> (diferencias en el grosor de la sección transversal de una misma película) y <u>entre distintas membranas</u> (diferencias en el grosor de las películas que han sido moldeadas con exactamente la misma configuración).

Pero, ¿por qué aparecían estos tipos de heterogeneidades La respuesta a esta pregunta es muy lógica: como la forma de moldeo de las películas no era consistente, los electrodos de batería obtenidos como resultado tampoco lo eran. En este contexto, el problema fundamental era que el proceso de moldeo manual introducía velocidades inconsistentes (no constantes) e inestabilidades que se correlacionaban con la variabilidad en el grosor de la membrana Por lo tanto, la misión de este proyecto era proporcionar al laboratorio de investigación de un proceso automatizado para moldear de manera consistente los electrodos de la batería.
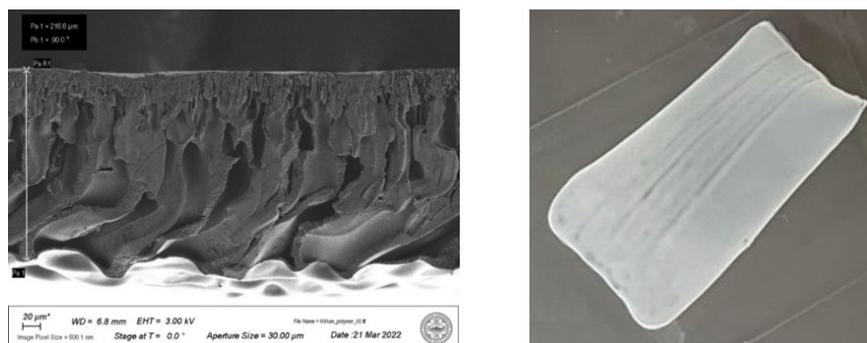

Ilustración 1: Electrodos de batería

Los principales objetivos del aparato automatizado eran:

- Espesor ajustable. El aparato automatizado tenía que proporcionar películas moldeadas con un grosor de entre 100 y 600 μm.
- Espesor consistente entre los ajustes. Si el aparato buscaba una película de 200 μm, era aceptable que la membrana resultante tuviera un grosor de 190 μm siempre que todas las membranas producidas con ese grosor preestablecido fueran de 190 μm.
- Velocidad constante y ajustable en el proceso de moldeo. La velocidad durante el colado debía ser constante y variable entre 5 - 40 mm/s.
- Poder sostener un cristal de ensayo como base de moldeo de 75 x 50 x 1,5 (largo x ancho x alto).
- Debía tener en cuenta las variaciones en el grosor de los cristales de ensayo. Los cristales de ensayo tienen imperfecciones y las tolerancias asociadas a ellos pueden afectar al grosor de la sección transversal del electrodo de batería.
- Poderse limpiar. Como la solución de trabajo (DMSO) es muy corrosiva, el aparato debía poder limpiarse manualmente.

Pero el aparato, además, tenía otros requisitos y limitaciones. El más exigente era el de que el proyecto estaba sujeto a un presupuesto de sólo 400$. Aunque esto pueda parecer mucho, en realidad no se tiene en cuenta que al dispositivo final se le pedían más funciones que otras opciones del mercado pero con un presupuesto al menos 10 veces menor.

Antes de explicar qué tecnología podría utilizarse actualmente para resolver el problema de consistencia al que se enfrentó el laboratorio del profesor Werner durante el moldeo de las membranas, es importante entender cómo se realizaba este proceso antes de construir el aparato.

1) La solución viscosa (normalmente DMSO: dimetilsulfóxido) se añadía al cristal de ensayo.
2) El moldeo de la película se realizaba con una cuchilla de moldeo. Tras el proceso, la película se dejó en reposo durante un tiempo determinado (alrededor de 1 minuto).
3) El cristal se introducía en el agua en un ángulo tal que rompiera la tensión superficial del agua. Tras unos 20 s dentro, el DMSO reaccionaba con el agua y se formaba la membrana polimérica.

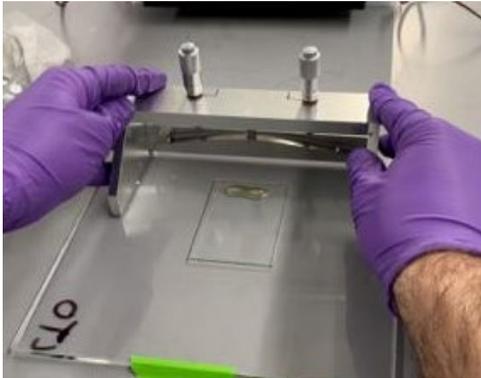**4)** Se extraía el portaobjetos del agua y se separaba la membrana del portaobjetos para analizarla.

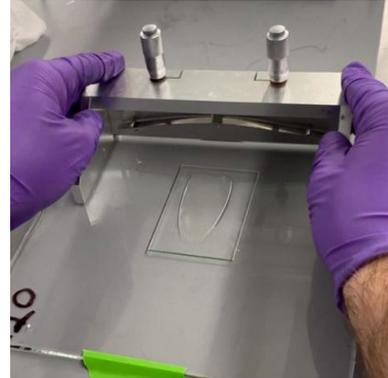*Ilustración 2: Solución en cristal de ensayo*

Ilustración 3: Moldeo

Ilustración 4: Precipitado

Ilustración 2: Formación membrana

Ilustración 6: Análisis

Antes de la existencia del aparato, para controlar el grosor real de las membranas que estaban estudiando, el laboratorio de Werner compró primero la que iba a ser la pieza más importante del diseño del dispositivo automatizado que necesitaban: una cuchilla de moldeo. Se trataba de una cuchilla para moldear películas, de la empresa *BYK Instruments* (835$), y puede verse en las figuras de arriba.

Además, para alcanzar una mayor consistencia, también se investigaron los aparatos automatizados de moldeo de películas del mercado. En ese proceso se vio claramente que la decisión más importante que debía tomar cada una de las diferentes opciones del mercado era la elección de una referencia de movimiento. Esto llevaba a tener que tomar la siguiente elección: mantener el cristal de ensayo inmóvil mientras la cuchilla estaba en movimiento o viceversa. Además, cada uno de los dispositivos de moldeo que se encuentran en el mercado cuentan con

maneras distintas de fijar el sustrato a la referencia y de solidificar la membrana moldeada. En cuanto a la cuchilla, las decisiones de diseño más importantes tenían que ver con la forma de la superficie de moldeo, el material de fabricación y la forma de ajustar el grosor de moldeo. Aunque estas opciones del mercado eran un buen material de investigación, su precio era demasiado elevado (+4.000 $) para considerarlas como una verdadera referencia.

2. Metodología

Para llegar a un dispositivo que pudiera moldear electrodos de batería consistentes, había que abordar dos tipos de diseños, el mecánico y el electrónico. El diseño mecánico proporcionaba al dispositivo los medios necesarios para que el proyecto tuviera éxito, mientras que el electrónico los automatizaba y garantizaba la consistencia.

Diseño Mecánico:

Como se ha dicho en la introducción, las dos primeras cosas que había que decidir en cuanto al diseño mecánico eran la definición del movimiento y el diseño de la cuchilla. En cualquier dispositivo de moldeo debe haber una parte que debe ser estática (referencia) y debe haber una parte que debe estar en movimiento. En el diseño preliminar se decidió que el cristal de ensayo iba a ser la parte en movimiento mientras que la cuchilla iba a permanecer inmóvil. En cuanto al diseño de la cuchilla, se eligió una superficie de moldeo circular por ser precisa y más fácil de mecanizar. La planificación general que siguió el prototipo preliminar se describe en la siguiente figura. El usuario preestablecería el proceso colocando en el cristal de ensayo la solución y luego el éste comenzaría a moverse hasta alcanzar una velocidad constante. A continuación, se realizaría el proceso de moldeo propiamente dicho en el que la cuchilla estaría inmóvil. Finalmente, el proceso terminaría empujando el cristal a través de una rampa hacia el baño de agua.
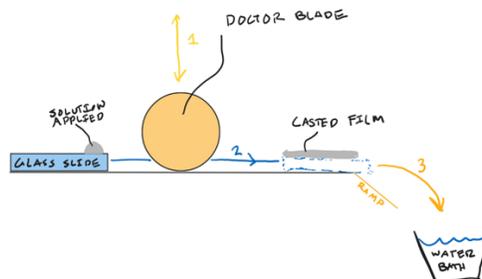

Ilustración 3: Diseño preliminar

El problema de tener la rasqueta estacionaria era que cuando el cristal de ensayo tenía que pasar por debajo de la cuchilla para fundir la película, tenía que empujar a la misma hacia arriba. Esto obligó a diseñar una cuchilla de moldeo más ligera, lo que provocó que la tensión superficial del DMSO jugara un papel diferencial debido a la alta viscosidad del líquido. Además, esta configuración inicial no sólo no tenía en cuenta las variaciones del grosor de los portaobjetos, sino que también había un problema de estabilidad entre los extremos de las láminas moldeadas. Para resolver todos estos problemas, se implementó un mecanismo de resorte (a través de muelles) en la cuchilla para ejercer la presión exacta hacia abajo para moldear en el espesor deseado. En las siguientes figuras se pueden apreciar las diferentes iteraciones de prototipos de este diseño preliminar.
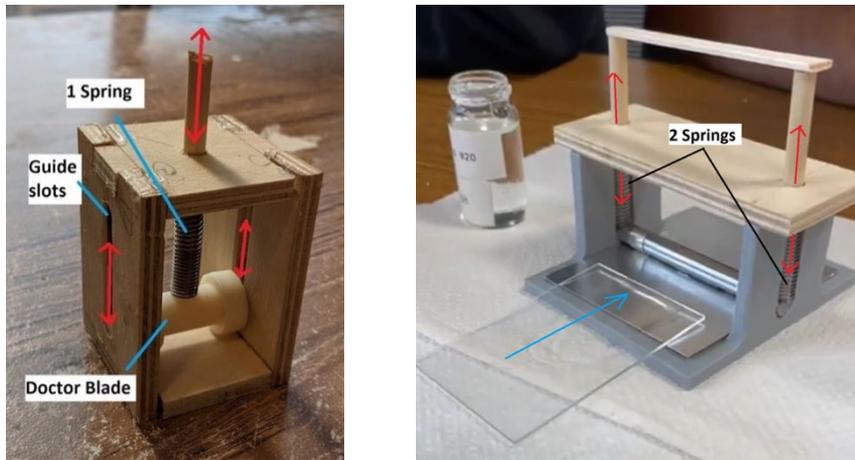

Ilustración 4: Detalle de prototipos 1 y 2

En la tercera iteración del prototipo, se implementó el movimiento lineal automatizado a una velocidad constante utilizando un motor paso a paso y un tornillo de avance. El diseño consistía en empujar el cristal de ensayo a través de la cuchilla mediante pasadores. Este diseño permitió

Ilustración 5: Detalle de prototipo 3

empujar el cristal por debajo de la cuchilla, moldear la película y salir directamente del aparato hacia un baño de agua en un movimiento lineal.

Sin embargo, empujar el cristal de ensayo acabó planteando una serie de problemas. En primer lugar, el cristal de ensayo sólo tiene 1,5 mm de grosor, lo que significa que los pasadores que lo empujaban debían ser inferiores a 1,5 mm, suponía un reto de tolerancia. El mayor problema era que las ranuras de la parte superior del conjunto permitían que la solución (DMSO) se filtrara en en su interior, lo que hacía que el diseño no se pudiera limpiar. Además, las ranuras también debilitaban la cubierta superior de la estructura, haciéndola más susceptible de romperse si no se manipulaba correctamente.

Para resolver el problema de las fugas de DMSO en la ranura, así como el debilitamiento de la pieza superior del conjunto, las ranuras se eliminaron por completo. Como resultado, el procedimiento de moldeo se cambió a un diseño optimizado en el que el cristal de ensayo estaba inmóvil y la cuchilla estaba en movimiento. Este método optimizado se muestra a continuación:

Ilustración 6: Diseño optimizado

1. El portaobjetos se mantiene inmóvil mediante un borde que ejerce de muro en la tapa superior del conjunto y la solución se aplica sobre el cristal de ensayo.
2. La cuchilla se coloca en el cristal de ensayo (con un grosor determinado) contra la barra de empuje y avanza linealmente moldeando la película.
3. A continuación, se despliega un mecanismo de empuje (representado en naranja) y se invierte el movimiento la barra, dejando atrás la cuchilla. A continuación, se empuja el cristal de ensayo hacia un baño de agua para solidificar la película.

En este diseño final, para mover la cuchilla por un cristal de ensayo, se utiliza una barra de empuje impresa en 3D. Esta barra de empuje está unida directamente al motor paso a paso. Tras el proceso de moldeo, en el que el cristal se mantiene fijo mediante el borde, la barra de empuje se deja caer

hasta una posición inferior. A continuación, mediante unas bisagras, empuja el cristal y lo introduce en el baño de agua gracias a una rampa impresa en 3D.

En cuanto al diseño de la cuchilla de moldeo, se utilizó una de 4 caras de forma circular para moldear la solución de DMSO con un grosor determinado. El diseño consiste en un cilindro de acero descentrado ajustado a presión entre dos bloques de aluminio, con agujeros realizados mediante EDM (*electrical discharge machine*). Como el cilindro interior no está centrado en los bloques de aluminio, se obtienen 4 opciones de moldeo de diferentes espesores disponibles para los clientes: 100, 200, 400 y 600 micras. Este diseño se asentaría directamente en el cristal de ensayo al principio del proceso de moldeo y se empujaría mediante la barra.
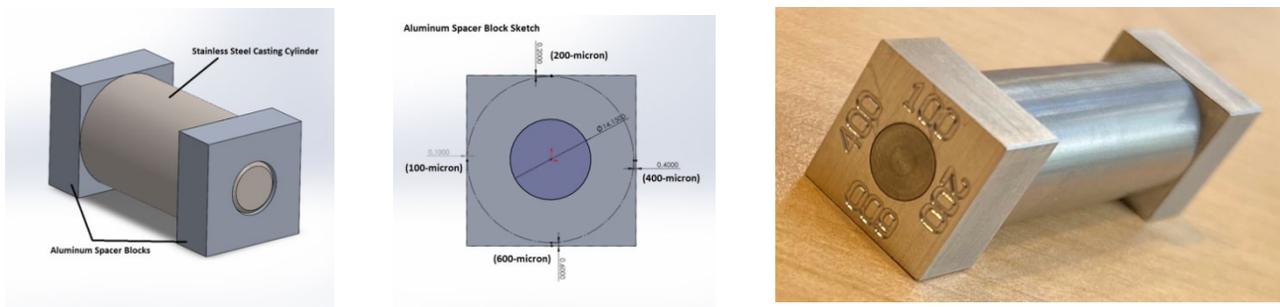

Ilustración 7: Diseño cuchilla de moldeo

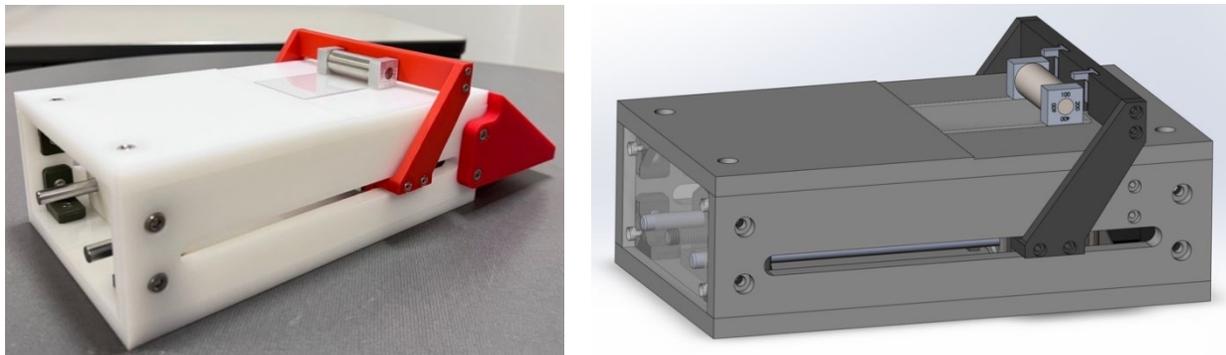Por tanto, el diseño optimizado fue modelado como se muestra en las siguientes figuras:

Ilustración 8: Detalle diseño mecánico

Diseño Electrónico:

Este diseño adicional es fundamental para cumplir los requisitos del proyecto que hacen de él un aparato automatizado y aseguran la consistencia necesaria en los electrodos de batería. Estos requisitos se pueden clasificar en requisitos de resultados (medios electrónicos para cumplir con el moldeo) y requisitos de interfaz de usuario (proporcionar al cliente una forma intuitiva de utilizar el dispositivo).

En cuanto a los requisitos de los resultados, el movimiento lineal a velocidad constante se consiguió con un motor paso a paso (*Nema 17*) tal y como se ha introducido en el diseño mecánico. Además, la homogeneidad necesaria durante el proceso de fundición hizo que fuera crucial tener un movimiento suave, lo que se logró utilizando un controlador de motor. Después de iterar entre dos modelos, se eligió el controlador de motor *A4988* ya que introducía una técnica llamada *microstepping* que hacía el movimiento mucho más suave. Por último, para hacer que la velocidad fuera variable y ajustable para el usuario se consideraron varios métodos. Un potenciómetro de 10kΩ (*RV24IN 20S/B103*) acabó siendo la forma más intuitiva y sencilla de cumplir este requisito.

Por otro lado, en cuanto a los requisitos de la interfaz de usuario, se utilizó una pantalla LCD como método de comunicación entre el aparato y el mismo, ya que este componente se configuró para ser el que mostrara las diferentes opciones de velocidad de moldeo cuando el usuario girara el potenciómetro. Además, para hacer funcionar el aparato se implementaron dos pulsadores, uno para cada sentido del movimiento (moldeo y retroceso). Además, como los clientes pidieron que el aparato fuera totalmente seguro, se les proporcionó un botón adicional (botón STOP) que podía detener la máquina cada vez que se pulsaba. Por último, como el movimiento debía estar acotado para evitar problemas mecánicos, se implementó un tope mecánico en ambos extremos de las direcciones de movimiento que pudiera detener inmediatamente el aparato cuando fueran presionados por la estructura. El circuito resultante se muestra a continuación:
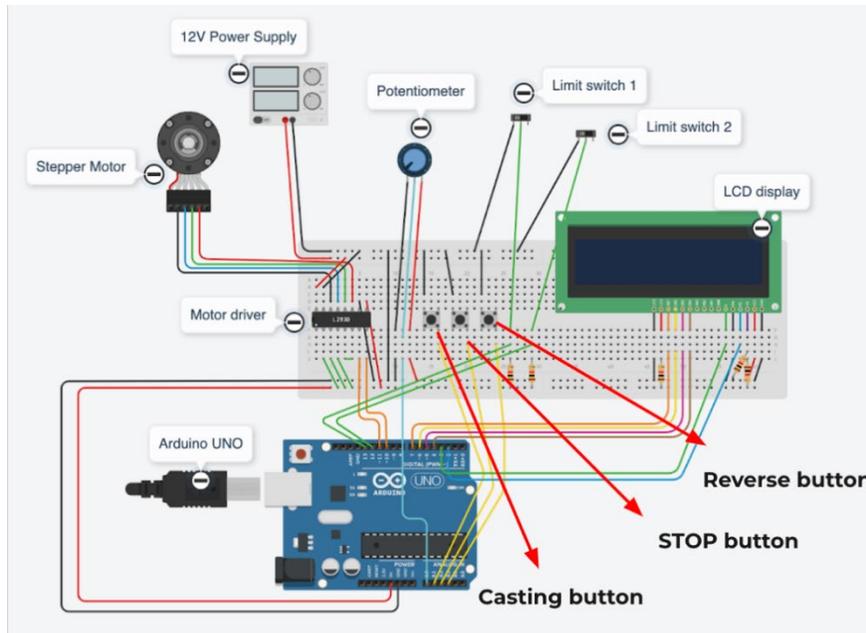
Ilustración 9: Circuito final

Se codificó todo el circuito y el sistema acabó funcionando como se esperaba. Sin embargo, para cumplir con la seguridad y la durabilidad solicitadas para el aparato, todos los componentes electrónicos se soldaron. Además, se empaquetaron y atornillaron dentro de una caja de electrónica que acabó formando parte de la estructura principal del aparato. El ángulo en el que se diseñó la caja electrónica hizo que el aparato tuviera una interfaz cómoda para ser utilizada por los clientes y la propia caja hizo que el diseño fuera mucho más compacto.
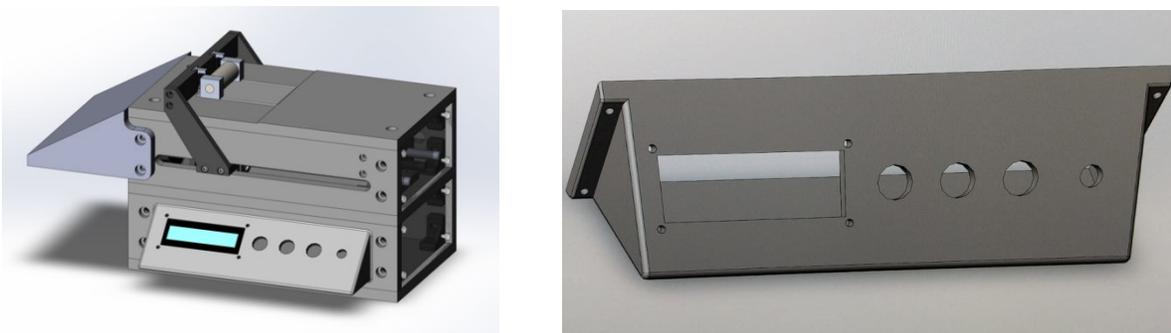
Ilustración 10: Detalle caja electrónica

3. Resultados

Los resultados de todos los avances en el diseño mecánico y electrónico se muestran en las imágenes de abajo:
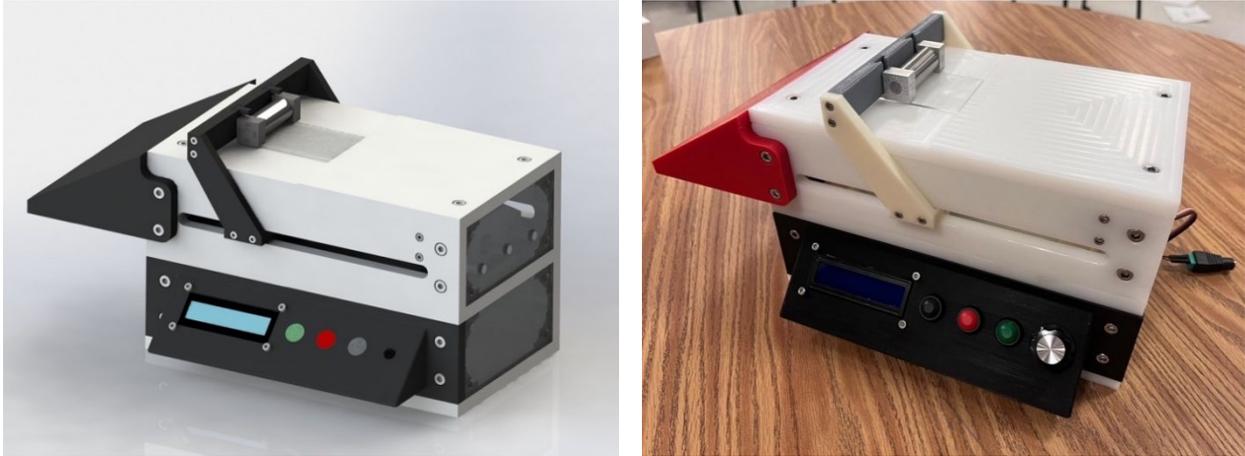
Ilustración 11: Comparación CAD y resultado

Ilustración 12: Progreso mecánico y electrónico
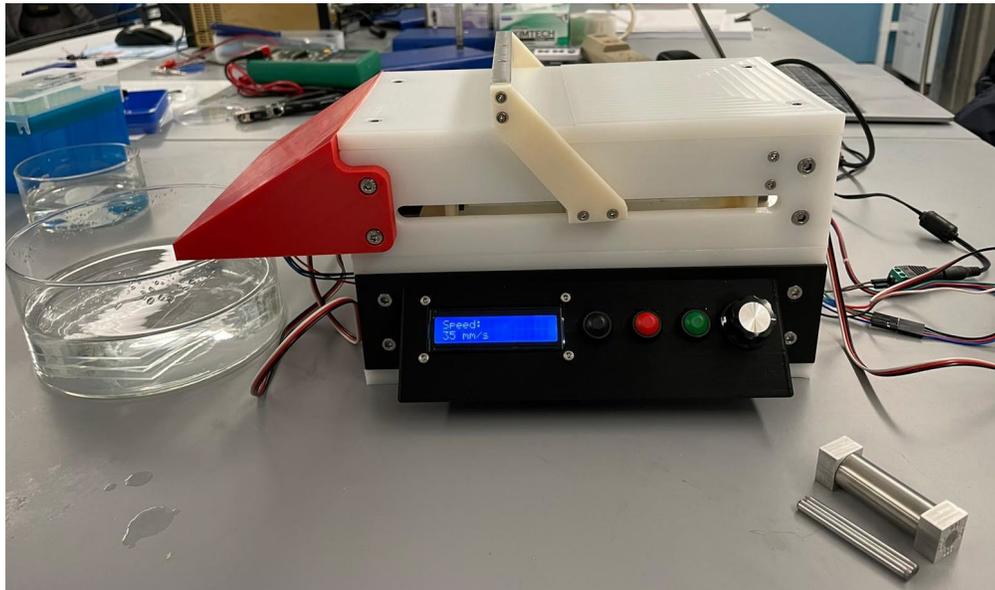
Ilustración 13: Aparato final

Aunque el diseño final tenía buena apariencia, esto no era suficiente. El objetivo principal del proyecto era conseguir un dispositivo automatizado que pudiera moldear electrodos de batería homogéneos a una gama de velocidades y espesores constantes variables utilizando una cuchilla. Para demostrar la funcionalidad del dispositivo se realizaron dos pruebas diferentes:

1. La primera fue una prueba de moldeo manual de la cuchilla fabricada para verificar que cumplía con el rango de espesores, la precisión y la consistencia de las membranas solicitadas. Para realizar las pruebas se utilizó un Microscopio Electrónico de Barrido (*SEM*) especializado. Antes de mostrar los resultados, es importante hacer saber al lector que, una vez moldeadas las películas y colocadas en un baño de agua para su solidificación, éstas se encogen. Por ello, como se ha dicho anteriormente, el objetivo de los diferentes espesores de moldeo no es obtener una membrana solidificada de, por ejemplo, 100 micras, sino una membrana de espesor uniforme por debajo de las 100. Las dos imágenes siguientes fueron el resultado del moldeo de una membrana de 100 micras:
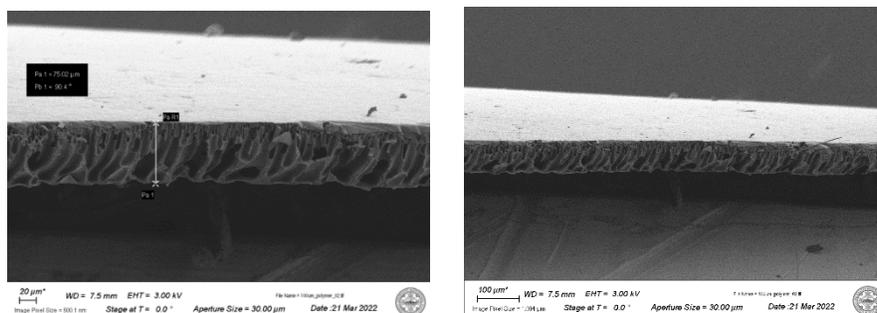
Ilustración 14: Resultado membranas moldeo manual

Los resultados fueron bastante satisfactorios, ya que la superficie era suficientemente plana y la sección transversal era muy homogénea. Sin embargo, los clientes estaban de acuerdo en que los resultados aún podían mejorarse eliminando las pequeñas burbujas que se formaban en la parte superior de la membrana debido a las aceleraciones que se producen en un proceso de moldeo manual. Para comprobarlo, era necesario el dispositivo automatizado.

2. Una vez ensamblados los diseños electrónicos y mecánicos, el dispositivo estaba listo para la prueba final. Se siguió el mismo procedimiento de *SEM* y los resultados fueron los siguientes:
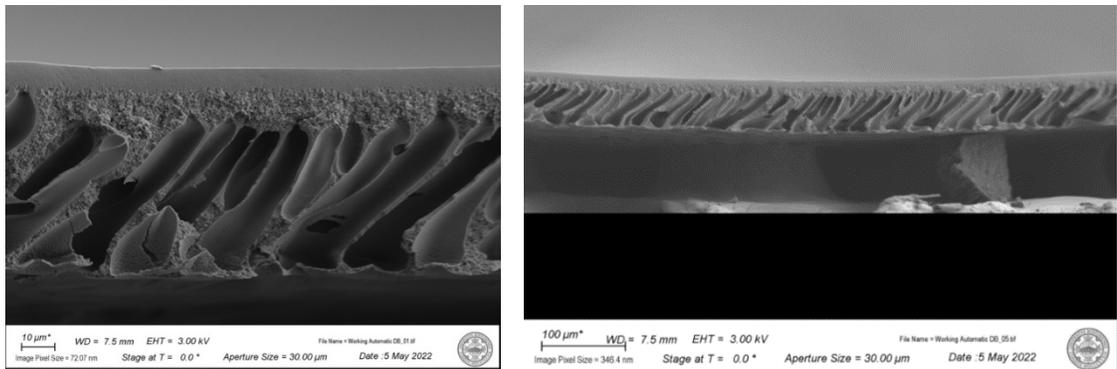
Ilustración 15: Resultado membranas moldeo automatizado

A simple vista los resultados pueden parecer muy similares a los de la prueba manual, sin embargo, no lo fueron. Las membranas fundidas con el dispositivo automatizado eran mucho más planas y no presentaban las grietas que se pueden observar en la ilustración 18. Además, cuando se comprobaron las burbujas anteriormente indicadas el resultado fue interpretado como muy exitoso por los clientes porque incluso a una escala de 1 µm las burbujas se habían reducido exponencialmente como se muestra en la siguiente figura:
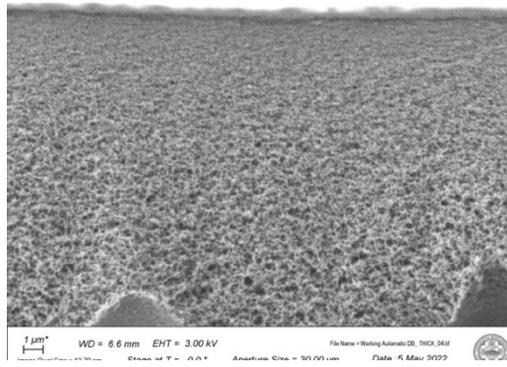
Ilustración 16: Detalle de burbujas en superficie

4. Conclusiones

La conclusión más importante que hay que extraer y la que resume los resultados es que, en definitiva, se logró la función del proyecto, moldear electrodos de batería submilimétricos. El dispositivo fue capaz de deslizar rápidamente la cuchilla por un cristal de ensayo con una solución viscosa encima. Una vez moldeada la membrana, el cristal de ensayo se empujaba hacia afuera del aparato y se introducía en un baño de agua. A continuación, el cliente sacaba el cristal de ensayo del baño de agua y evaluaba una sección transversal del electrodo con un microscopio electrónico de barrido (SEM). Los clientes informaron de que los resultados superaban sus pruebas y eran consistentes en todo momento.

Hay que recordar el objetivo más importante del proyecto: proporcionar a los clientes un dispositivo automatizado que les ayudara a alcanzar la consistencia que necesitaban en los electrodos de las baterías para poder realizar sus investigaciones posteriores. Este objetivo se logró, ya que los electrodos de batería moldeados en las pruebas finales resultaron ser homogéneos no sólo en su sección transversal, sino también entre las diferentes membranas que se moldearon.

Al comprobar otros objetivos que el cliente se planteó al principio del proyecto, se puede decir que el dispositivo resultante es un verdadero éxito:

- Puede moldear electrodos de batería a diferentes grosores dejando que el usuario lo preajuste.
- Hay un grosor consistente entre los ajustes, lo que significa que diferentes electrodos de batería moldeados con el mismo grosor acaban siendo muy homogéneos entre sí.
- El dispositivo es capaz de moldear a una velocidad constante evitando la formación de burbujas en la superficie superior de los electrodos de batería moldeados.
- El dispositivo permite al usuario elegir la velocidad a la que se va a moldear el electrodo de batería en el rango preestablecido de 5 - 40 mm/s.
- La posición inicial de la cuchilla de moldeo (parte superior del cristal de ensayo) hace que el producto final tenga en cuenta la variabilidad del espesor del cristal de ensayo, asegurando que no afecte al espesor final de la membrana.

- El dispositivo permite su fácil limpieza ya que la cuchilla de moldeo finalmente no es estacionaria y se puede retirar fácilmente para su limpieza y la de la superficie superior del aparato.
- El aparato es capaz de trabajar con el tamaño del cristal de ensayo indicado al principio del proyecto: 75 x 50 x 1,5 (L x A x H).

AUTOMATED MEMBRANE CASTING APPARATUS FOR NOVEL ENERGY STORAGE ARCHITECTURES

Author: Sánchez-Cantalejo Hevia, Ángel.
Supervisor: Gutiérrez-Wing, Enrique S..
Collaborating Entity: Boston University – Mesostructured Materials and Devices Lab (MeMaD)

ABSTRACT

Keywords: Film casting, Battery Electrode, Consistency, Doctor Blade, Battery Research, Thickness, Automated

1. Introduction

Boston University's Professor Jörg Werner, Ph.D., is the main customer of this project together with his collaborator Anton Resing (graduate student). Prof. Werner's research is focused on functional materials and devices with nano-to-microscale structures enabled by molecular self-assembly, phase separation, and other methods. He leads the Mesostructured Materials and Devices (MeMaD) lab where, with his collaborator Anton Resing, they are researching on the use of battery electrodes as an ion transportation method.

In September, Prof. Werner needed a device that could be used to fabricate hierarchically structured battery electrodes which result from a phase separation process that occurs when a cast polymer solution is immersed in a precipitation bath such as water. This process can be done by hand, but for the reproducibility necessary for systematic studies, an automated film casting apparatus with various control parameters was needed. Successful implementation of this device would result in battery electrodes that could serve as the architectural base for three dimensionally structured electrodes and batteries that have the potential to dramatically decrease the charge time of personal electronics, enable efficient on-chip energy storage, and play an influential role in the development of the internet of things. Once the device had been implemented, it would stay with the customers in the MeMaD lab to be used as a key material of their research.

The reason why it has previously been stated why Prof. Werner needs the apparatus for is to introduce what motivation followed the project. However, it is important to notice that this project has not been focused on the research on the battery electrodes that will serve as an ion

transportation method, but on the design and building of the apparatus that will provide the consistency needed to do that research.

The problem that Prof. Werner's lab was facing is that phase inversion membranes are subjected to variations due to inconsistencies in film casting. In September, there was no automated process for casting these membranes in his lab and that is why it was done by hand. This led to two types of inconsistencies: within films (differences in the thickness of the cross-section of a same film) and between films (differences in the thickness of films cast with the exact same configuration).

But why did these types of inconsistencies appear? The answer to this question is very logic: as the way in which the films were cast wasn't consistent, the battery electrodes obtained as a result weren't neither. In this context, the problem was that the manual casting process introduced inconsistent casting speeds and stability which correlated to variability in membrane thickness Hence, the mission of this project was to provide Prof. Werner's lab with an automated process to consistently cast the battery electrodes.
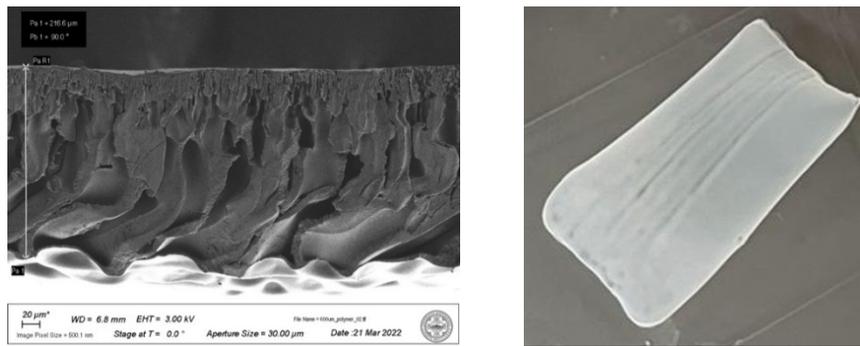
Figure 17: Detail of the membranes

The main objectives of the automated apparatus were:
- Adjustable thickness. The automated device had to provide cast films ranging from 100 – 600 μm in thickness.
- Consistent thickness between adjustments. If the apparatus aimed a film of 200 μm, it was acceptable if the resulting membrane was 190 μm thick as long as all the membranes produced with that preset thickness were of 190 μm.
- Constant and adjustable velocity in the casting process. Speed while casting had to be constant and variable between 5 – 40 mm/s.

- Able to hold a glass slide as the casting substrate of 75 x 50 x 1.5 (L x W x H).
- Must account for variations in the thickness of the glass slides. Glass slides have imperfections and tolerances associated with them can affect the battery electrode's cross-sectional thickness.
- Cleanable. As the working solution (DMSO) is very corrosive, the device had to be manually cleanable.

But the apparatus, also had other requirements and constraints. The most demanding one was the that the project was subjected to a budget of only $400. Although this may sound as a lot, in fact it is not taking into account that the final device was asked to perform more functions than other market options but with a budget at least 10 times smaller.

Before explaining what technology could be currently used to solve the consistency problem that Prof. Werner's lab faced during the film casting, it is important to understand how this process was done before building the apparatus:

1) The viscous solution (typically DMSO: Dimethyl Sulfoxide) was added to the glass slide.
2) The film casting took place using a doctor blade. After casting, the film was left resting for a specified amount of time (around 1 minute).
3) The glass slide was put/pushed into water at an angle so that it broke the superficial tension of water. After around 20 s inside the water, the DMSO reacted with the water and a polymeric membrane was formed.
4) The glass slide was extracted out of the water and the membrane was separated from the glass slide ready to be analyzed.
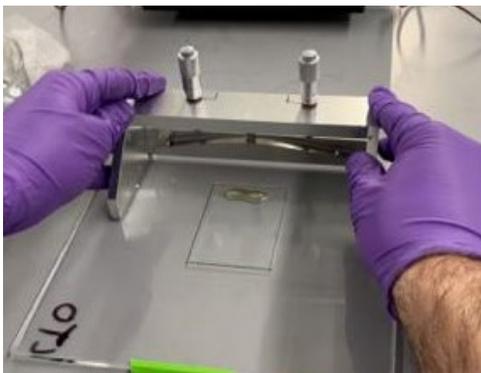
Figure 2: Solution
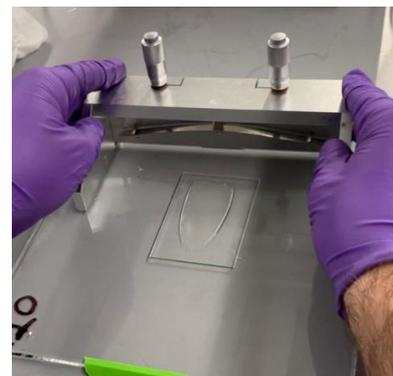
Figure 3: Casting process

Figure 4: Precipitation

Figure 5: Phase inversion

Figure 6: Analysis

Before the existence of the apparatus, to control the actual thickness of the membranes they were studying, the Werner's lab first bought what was going to be the most important piece to design of the automated device they needed: a doctor blade. It consisted of a film casting knife, from the company BYK Instruments ($835), that can be seen in the figures above.

In addition, to reach greater consistency, automated film casting apparatus from the market were also researched. In that process it was clearly seen that the most important decision that each of the different market options had to take was choosing a movement reference. This led to the following choice: keeping the glass slide stationary while the doctor blade is in movement or vice versa. In addition, each of the casting devices found in the market had to design a way to fixture the substrate to the reference and to solidify the cast membrane. Regarding the doctor blade, the most important design decisions involved the casting surface shape, the manufacturing material, and the way to adjust the casting thickness. Although these market options were good research material, their price was too high (+$4,000) to consider them as a true reference.

2. Methodology

In order to reach to a device that could cast consistent battery electrodes, there were two kinds of designs that had to be addressed, the mechanical design and the electronic one. The mechanical design provided the device with the means needed for the project to succeed, while the electronic one automated them and ensured the consistency.

Mechanical Design:

As stated in the introduction, the first two things that had to be decided in terms of the mechanical design were defining the movement and the doctor blade layout. In whichever casting device there

must be a part that must be static (reference) and there must be a part that has to be in movement. In the preliminary design it was decided that the glass slide was going to be the moving part while the doctor blade was going to stay stationary. Regarding the doctor blade, a circular casting shape was chosen as it was precise and easier to machine. The general planning that the preliminary prototype followed is described in the following figure. The user would preset the process placing in the glass slide the solution and then the glass slide would start moving until reaching a constant speed. This would be followed by the actual casting process in which the doctor blade would be stationary. The process would finally end up by pushing the glass slide down through a ramp into the water bath.
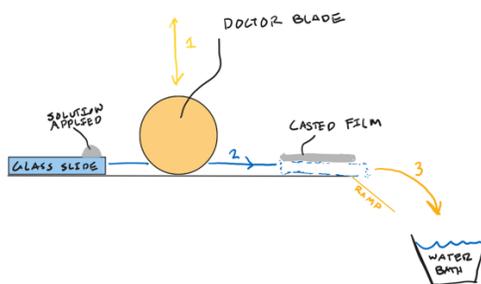
Figure 7: Preliminary design

The problem of having the doctor blade stationary was that when the glass slide had to pass under the doctor blade to cast the film, it needed to push the doctor blade up. This forced the design to have a lighter doctor blade which provoked that the surface tension of the DMSO played a differential role due to the high viscosity of the liquid. In addition, this initial configuration not only was not accounting for variations in glass slides' thickness, but also there was also an stability problem between the ends of the cast films. To solve all these problems, a spring-loaded mechanism was implemented in the doctor blade to make the exact pressure down to cast at the desired thickness. In the following figures, the different prototypes iterations of this preliminary design can be appreciated.
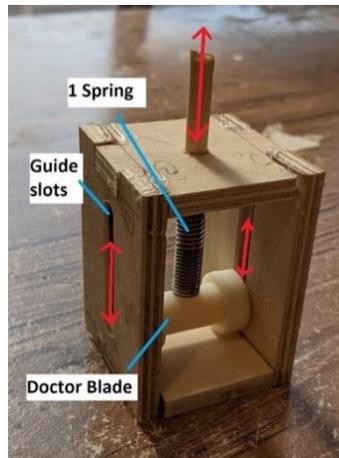
Figure 8: Prototype 1   Figure 9: Prototype 2
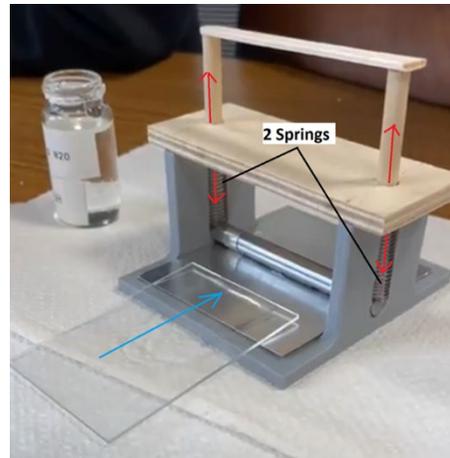
In the third prototype iteration, the automated linear movement at a constant speed was implemented using a stepper motor and a lead screw. The design consisted of pushing the glass slide through the doctor blade using protruding pins. This design allowed for the slide to be pushed under the doctor blade, casting the film, and straight off the apparatus into a water bath in one linear motion.
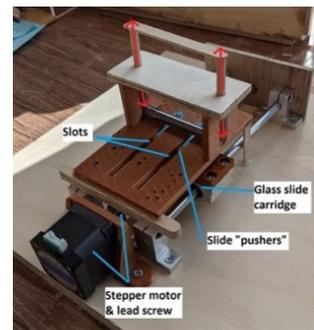
Figure 10: Prototype 3

However, pushing the glass slide ultimately posed a number of problems. First, the glass slide is only 1.5 mm thick which meant that the pins that pushed the slide had to be under 1.5mm which posed a tolerancing challenge. The biggest problem was that the slots at the top of the assembly allowed for the casting solution (DMSO) to leak into the assembly which would make the design

not cleanable. On top of that, the slots also weaken the top cover of the assembly making it more susceptible to snapping if not handled properly.

To solve the problem of the DMSO leaking into the slot as well as weakening the top piece of the assembly, it was removed completely. As a result, the casting procedure was changed to an optimized design in which the glass slide was stationary and the doctor blade was in movement. This optimized method is shown below:

1. The glass slide is kept stationary by using a milled down lip in the top cover of the assembly and the solution is applied onto the slide.
2. The doctor blade is placed on the glass slide (at a prescribed thickness) against the push bar and advances linearly casting the film.
3. A 'plow' mechanism (shown in orange) is then deployed and the push bar is reversed, leaving the doctor blade behind. The plow then pushes the glass slide off into a water bath to solidify the film.
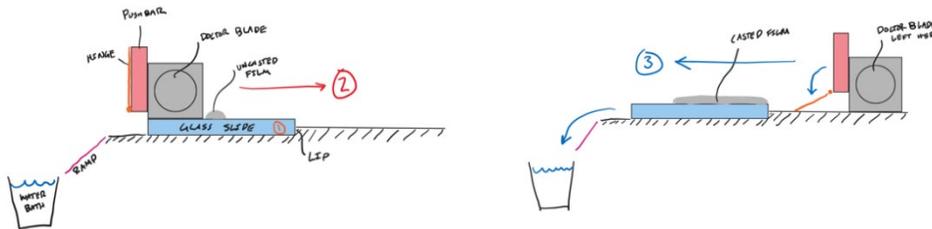
Figure 11: Optimized design

In this final design, to move the doctor blade across a glass slide, a 3D printed push bar is used. This push bar is attached directly to a stepper motor. After the casting process, in which the glass slide remains stationary using a lip, the push bar is dropped to a lower position. Then, using hinges it pushes the glass slide off of the device and into the water bath thanks to a 3D printed ramp.

Regarding the doctor blade design, a circular shaped 4-Sided doctor blade was used to cast the DMSO solution to a specified thickness. The design consists of an off-centered steel cylinder press fit between two aluminum blocks, with holes using wire EDM. As the inner cylinder is not centered in the aluminum blocks, it results in 4 different thickness casting options available for the customers: 100, 200, 400, and 600 microns. This design would sit directly onto the glass slide at the beginning of the casting process and be pushed off using a push bar.
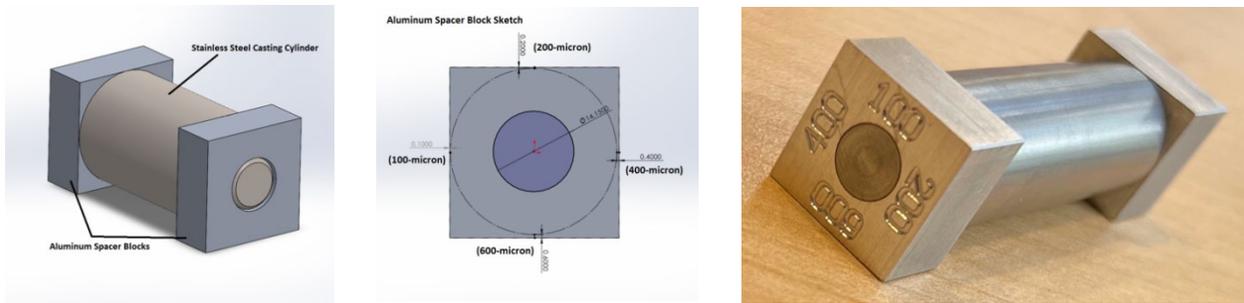
Figure 12: Doctor blade desing

Therefore, the optimized design looked as in the following figure:
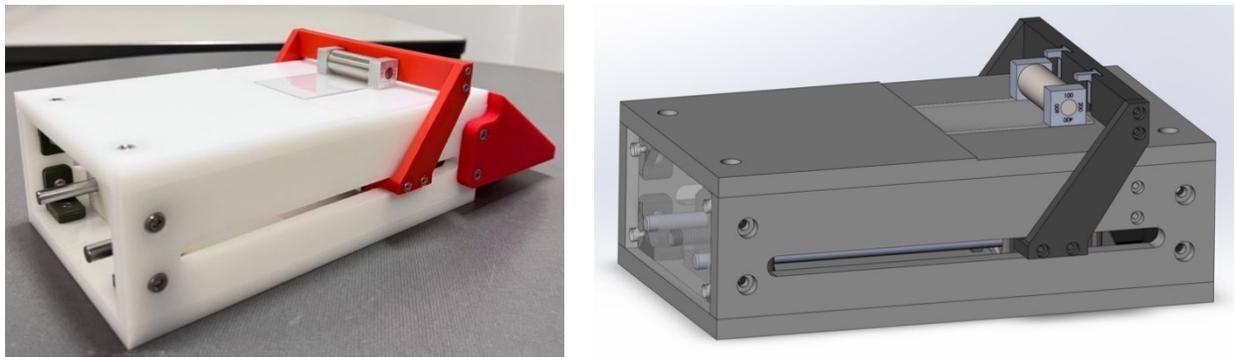
Figure 13: Mechanical Design

Electronics Design:

This additional design is fundamental to fulfill the requirements of the project that make of it an automated apparatus and ensure the consistency needed in the battery electrodes. These requirements can be classified in results' requirements (electronic means to fulfill functions) and user interface requirements (provide the customer with an intuitive way to use the device).

Regarding the results' requirements, the linear motion at a constant speed was achieved with a stepper motor *(Nema 17)* as it has been introduced in the mechanical design. In addition, the homogeneity needed during the casting process made crucial to have a smooth movement which was accomplished using a motor driver. After iterating between two models, the *A4988 motor driver* was chosen as it introduced a technique called microstepping which made the movement much smoother. Finally, to make the speed variable and adjustable for the user a couple of methods

were considered. A 10kΩ potentiometer (*RV24IN 20S/B103*) ended up being the most intuitive and simple way to fulfill this requirement.

On the other hand, regarding the user interface requirements, an LCD display was used as a communication method between the apparatus and the user as this component was configured to be the one that showed the different casting speed options when the user spined the potentiometer. Also, to make the apparatus work two push buttons were implemented, one for every direction of the movement (casting and reverse). In addition, as the customers asked for the device to be totally safe, they were provided with an additional button (STOP button) which could stop the machine whenever it was pressed. Finally, as the movement had to be bounded to avoid mechanical issues, a mechanical endstop was implemented in both ends of the movement directions which could immediately stop the movement when they were pressed by the moving structure. The resulting circuit is shown below:
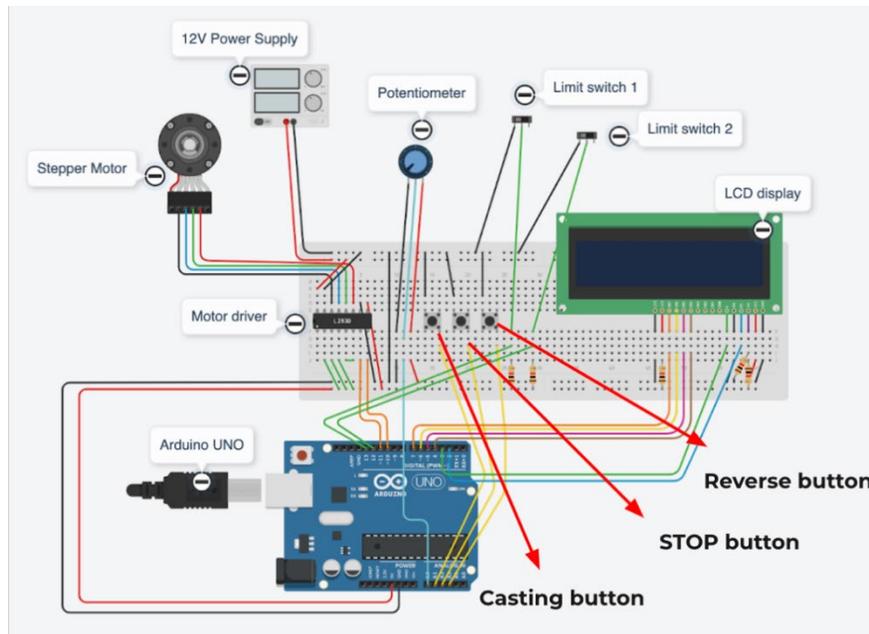
Figure 14: Final circuit

The whole circuit was coded, and the system ended up working as expected. However, to comply with the requested safety and durability of the apparatus, all the electronic components were soldered. In addition, they were packed and screwed inside an electronic box which ended up being part of the main structure of the apparatus. The angle in which the electronics box was designed

made the apparatus have a comfortable interface to be used by the customers and the box itself made the design much more compact.

Figure 15: Electronic box

3. Results

The results of all the mechanical and electronics design progress are showed in the images below:
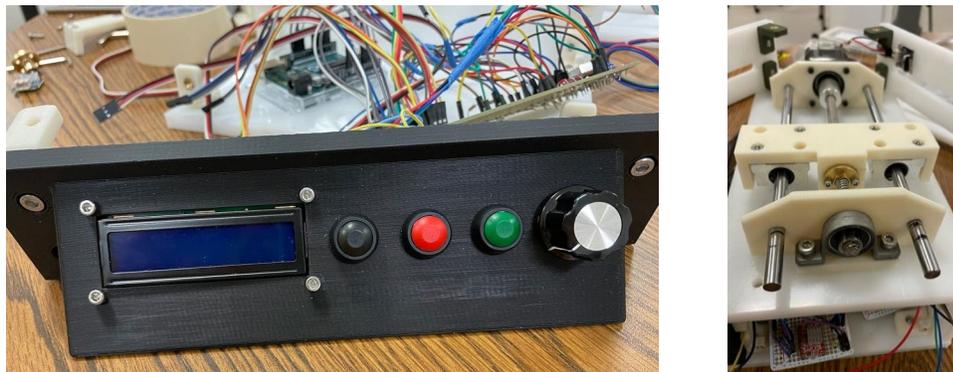
Figure 16: Mechanical and electronics design's details
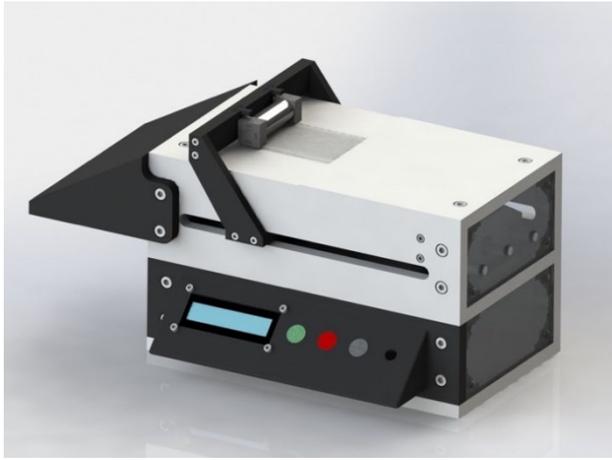
Figure 17: Comparison between CAD and final product
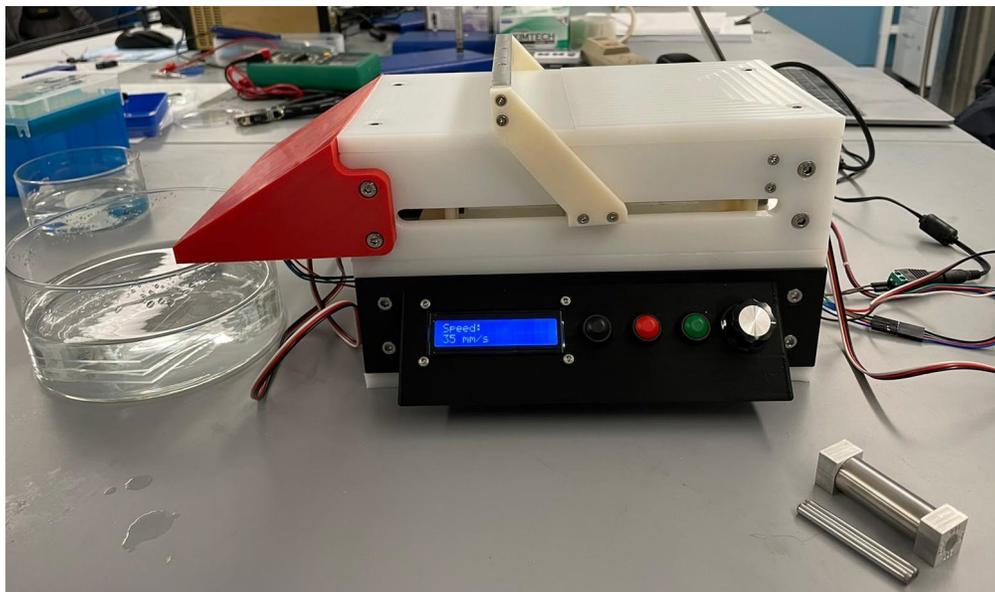
Figure 18: Final device

Even though the final design seemed to have good appearance, this was not enough. The main objective of the project was to achieve an automated device that could cast homogeneous battery electrodes at a range of variable constant speeds and thicknesses using a doctor blade. To prove the functionality of the device two different tests were executed:

1. The first one was a manual casting test of the manufactured doctor blade to verify that it complied with the range of thickness, precision and the membranes consistency requested. To perform the tests, an specialized Scanning Electron Microscope (SEM) was used. Before showing the results, it is important to let the reader know that once the films are

cast and placed in a water bath to solidify, they shrink. As a result of this, as previously stated, the aim of the different cast thickness is not to get a solidified membrane of, for example, 100 microns, but a uniformly thick membrane below 100 microns. The following two pictures were taken from a 100 microns membrane:
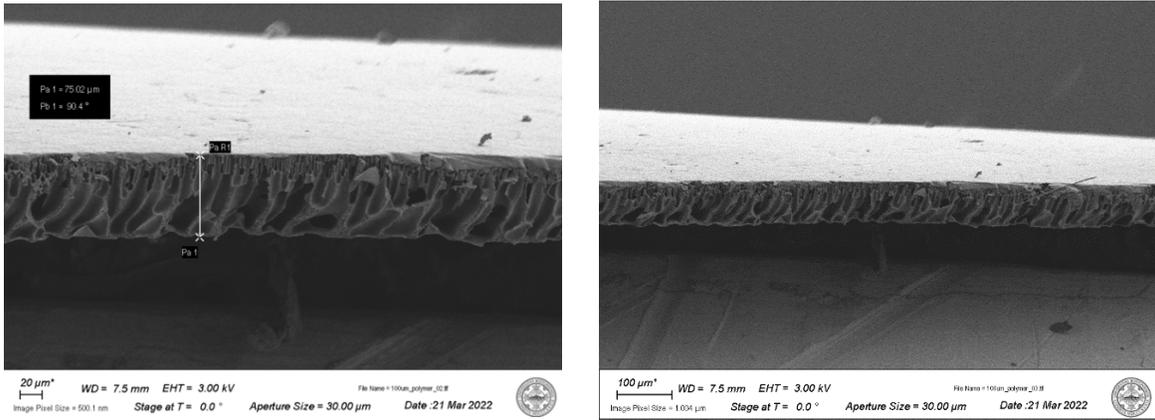
Figure 19: Cast membrane in manual method test

The results were quite successful as the surface was more or less flat and the cross-section was very homogeneous. However, the customers agreed that the results could still be improved eliminating the small bubbles that were formed in the top part of the membrane due to the accelerations that occur in a manual casting process. To test that the automated device was needed.

2. Once the electronics and mechanical designs were assembled together, the device was ready for the final test. The same SEM procedure was followed and the results were the following:
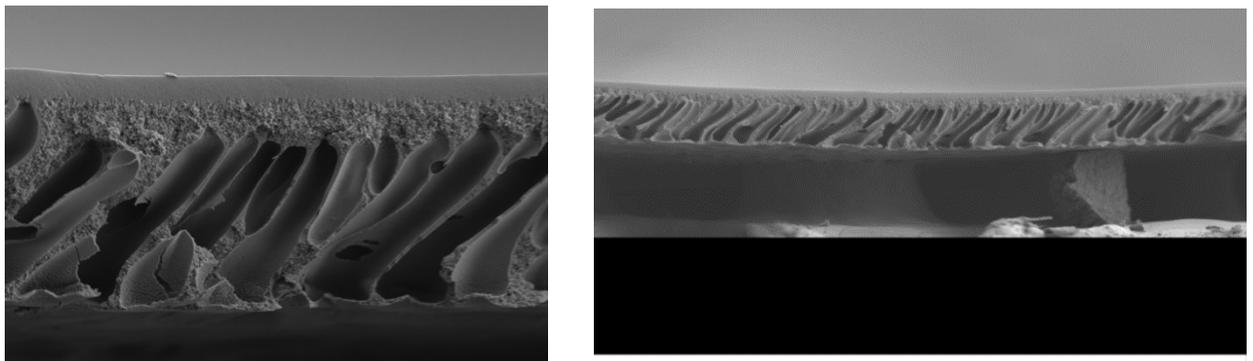
Figure 20: Cast membrane in automated method test

With a naked eye the results may seem very similar to the manual test, however, they were not. The membranes cast with the automated device were much flatter and they did not present the cracks that can be observed in illustration 41. In addition, when the previously stated bubbles were checked the result was interpreted as very successful by the customers because even at a scale of 1 μm the bubbles had been reduced exponentially as shown in the following figure:
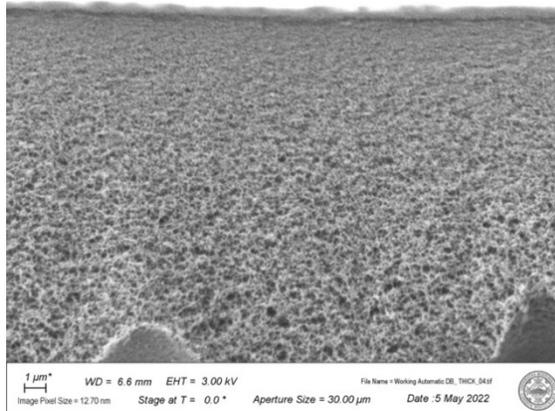
Figure 21: Detail of the bubbles

4. Conclusions

The most important conclusion to extract and the one that sums up the results is that, ultimately, the project function, casting sub-millimeter battery electrodes was achieved. The device was able to swiftly glide the doctor blade across a glass slide with a viscous solution on top of it. Once the solution was cast, the glass slide was pushed off of the apparatus and into a water bath. The customer then retrieved the glass slide from the water bath and evaluated a cross-section of the electrode using a scanning electron microscope (SEM). It was then reported that the results passed their tests and were consistent throughout.

The most important objective of the project must be remembered: providing the customers with an automated device that could help them to reach the consistency they needed in the battery electrodes in order to do their later research. This objective was achieved as the battery electrodes cast in the final tests turned up being homogeneous not only in their cross-section, but also between the different membranes that were cast.

When checking other objectives that the customer set up at the beginning of the project, it can be said that the resulting device is a real success:

- It can cast battery electrodes at different thickness letting the user presetting it.
- There is a consistent thickness between the adjustments, which means that different battery electrodes cast at the same casting thickness end up being very homogeneous between each other.
- The device is able to cast at a constant speed avoiding the formation of bubbles in the top surface of the cast battery electrodes.
- The device allows the user to choose the speed at which the battery electrode is going to be cast in the preset range of 5 – 40 mm/s.
- The initial position of the doctor blade (top of the glass slide) makes sure that the final product accounts for variability in the glass slide thickness, making sure that it does not affect in the final membrane's thickness.
- The device allows its easy cleanability as the doctor blade is finally not stationary and it can easily be removed for its cleanup and the one for the top surface of the apparatus.
- The device is able to work with the glass slide size stated at the beginning of the project: 75 x 50 x 1.5 (L x W x H).

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CHAPTER 1- INTRODUCTION

CHAPTER 1. INTRODUCTION

1.1 Context:

In the summer of 2021, I started checking the different projects that ICAI was suggesting to its students to take as *Trabajo de Fin de Grado (TFG)*. Before choosing one of those, I waited to see if I could possibly take part of a project proposed by what was going to be my future university for the following academic year 2021-2022, Boston University (BU). This was the recommendation that Professor José Ignacio Linares gave to future exchange students in his TFG presentation in April 2021.

In September 2021, following the recommendation of past exchange students from ICAI who had been in BU in previous years, I contacted Enrique S. Gutiérrez-Wing, Ph.D., professor at the College of Engineering and member of the Mechanical Engineering Department of BU. After explaining him the dynamics of the *TFG* in ICAI, he remembered past ICAI exchange students and, as he did with them in the past, he offered me to unofficially take part in the subjects ENG ME 460 and 461: Senior Design. Taking this subject, I was offered a wide list of different projects from Boston University I could take charge of.

I finally chose Project 23: *Automate Membrane Casting Apparatus for Novel Energy Storage Architectures*, together with two other students: Khalid Isahak and Aaron Pan. I chose Professor Gutiérrez-Wing as my Project Director and I reported this to ICAI through the *Anexo A*. Due to the mechanical engineering nature of the project, I asked Professor Eva María Arenas Pinilla to be the coordinator of the project. On the 6th of October of 2021, she accepted to be the coordinator, she approved the project as "valid", and she warned me I had to adapt this group project to the Spanish normative in which the project is individual.

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CHAPTER 1- INTRODUCTION

1.2 To whom and where:

Boston University's Professor Jörg Werner, Ph.D., is the main customer of this project together with his collaborator Anton Resing (graduate student). Prof. Werner's research is focused on functional materials and devices with nano-to-microscale structures enabled by molecular self-assembly, phase separation, and other methods. He leads the Mesostructured Materials and Devices (MeMaD) lab where, with his collaborator Anton Resing, they are researching on the formation of multi-functional, three-dimensionally mesostructured materials and the development of fully interdigitated complex device architectures such as three-dimensional solid-state batteries. This lab is located in Boston University's Charles River Campus and it is part of the university's mechanical engineering department. As stated, although the principal investigator is Prof. Werner, he is helped by a team of five graduate students (such as Anton Resing) and two undergraduate students.

Figure 1: Boston University's MeMaD logo [8]

In September, Prof. Werner needed a device that could be used to fabricate hierarchically structured battery electrodes which result from a phase separation process that occurs when a cast polymer solution is immersed in a precipitation bath such as water. This process can be done by hand, but for the reproducibility necessary for systematic studies, an automated film casting apparatus with various control parameters was needed. Successful implementation of this device would result in battery electrodes that could serve as the architectural base for three dimensionally structured electrodes and batteries that have the potential to dramatically decrease the charge time of personal electronics, enable efficient on-chip energy storage, and play an influential role in the development of the internet of things. Once the device had been implemented, it would stay with the customers in the MeMaD lab to be used as a key material of their research.

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CHAPTER 1 - INTRODUCTION

1.3 Mission

The reason why it has previously been stated why Prof. Werner needs the apparatus for is to introduce what motivation followed the project. However, it is important to notice that this project has not been focused on the research on the hierarchically structured membranes that will serve as architectural base for three dimensionally structured electrodes and batteries, but on the design and building of the apparatus that will provide the consistency needed to do that research.

The problem that Prof. Werner's lab was facing is that phase inversion membranes are subjected to variations due to inconsistencies in film casting. In September, there was no automated process for casting these membranes in his lab and that is why it was done by hand. This lead to huge inconsistencies. The mission of this project was to provide Prof. Werner's lab with an automated process to consistently cast these battery electrodes.

Although the project's objectives and functions will be explained in the following section of this document, it is important to introduce that the automated device will be able to: 1) Hold a viscous solution (0.05-0.5 mL) on a supporting substrate (25 x 75 mm) that is transiently fixed to the apparatus casting table. 2) Blade coat deposited solution on substrate to a specified thickness at a prescribed speed. 3) Expel substrate with cast solution into large bath of water after a prescribed time.

1.4 Important terminology

Before deepening into the motivation and development of the project there are some important terms that must be described and internalized to better understand the whole project:

- **Doctor blade.** It is probably the most important term of the project. Reaching to a proper design of this key element was determinant to the overall success of the project. It consists of a blade that is used to flatten a viscous solution to a desired thickness.

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CHAPTER 1- INTRODUCTION

Figure 2: Doctor Blade

- **Battery electrode.** This element is an electrical conductor which carries electric current, and which usually is in contact with a nonmetallic element of the circuit, in this case an electrolyte. It is an important term because it will be the production goal of this project as in Werner lab they use the battery electrodes as an ion transportation method. That is exactly where they want to research on. The electrodes cast in Werner's lab are composed of a viscous chemical solvent called DMSO (dimethyl sulfoxide). The battery electrodes will sometimes be referred as "membranes" because of their texture and shape.
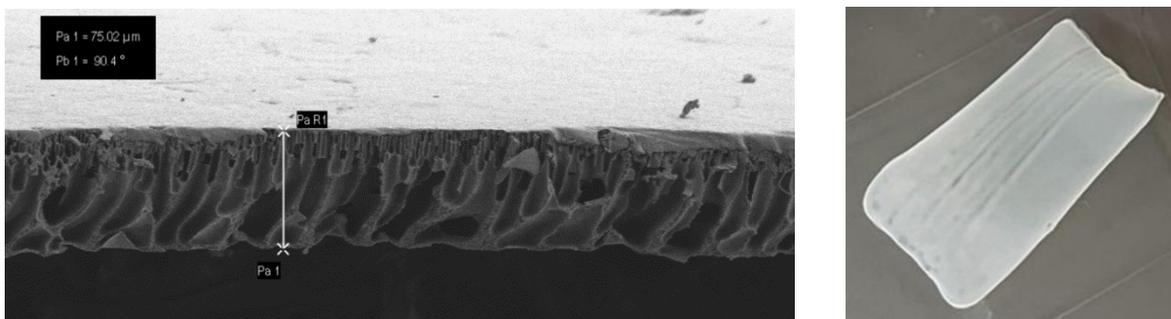
Figure 3: Detail of battery electrodes [9]

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CHAPTER 1- INTRODUCTION

- **To cast.** Although this verb has many meanings, during this project this verb will mean to mold and extend a certain substance to give to it a certain shape, that is to coat something using a certain process. It can be seen as a mix between the verbs "to spread" and "to mold". It is an important term that will be used during the whole memory.

- **Consistency.** It can be seen as the final and main objective of the whole apparatus. This term means homogeneity and repetitively and it will be used referring to the casting process of the battery electrodes.

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CHAPTER 2 - MOTIVATION

CHAPTER 2. MOTIVATION

It is easy to deduct the motivation of the project from last chapter (Introduction). However, this section will be used to briefly relapse on what are the most important considerations for the customer and which are the project objectives.

2.1 Problem definition

In September 2021, in the Werner lab, thin films were cast in order to be used as materials for battery research. These films were the result of a phase inversion method which is a process of controlled polymer transformation from a liquid phase to solid phase. Between the different techniques to create phase inversion membranes, the most widely used is immersion precipitation, which is graphically described in figure 4. The first step "polymer solution" represents the mix of polymer and solvent to form a solution. Then this solution is cast in a proper substrate, in this case a glass slide, using a doctor blade. Once the film is cast it is submerged inside a coagulation bath that contains nonsolvent (in this case water) where the precipitation process takes place due to the solvent and nonsolvent exchange. Hence, the membrane is formed and it is ready for a post-treatment (if needed) or for the later research on it. Although the phase inversion process has these four steps, this project is only going to focus on the middle two steps: casting the polymer film and the immersion in the precipitation bath.
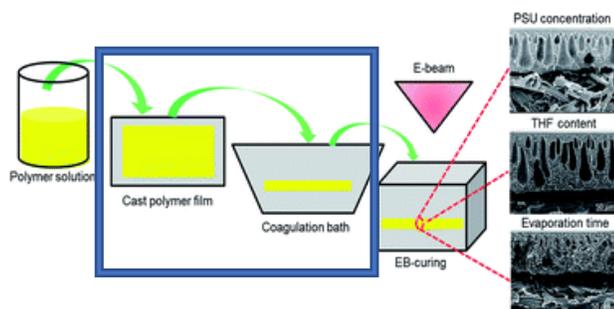
Figure 4: Phase inversión process diagram

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As explained in the introduction, the customers need these battery electrodes for battery research. When the project was described, the clients explained that the problem that they were having is that the method that they were using to cast the films lead to inconsistent battery electrodes that didn't allow them to reach to systematic results in the later research of the battery electrodes. When asked about what they meant with "inconsistent battery electrodes" their explanation was that the films that they cast in that time presented two types of inconsistencies:

- **Within films.** This meant that when a single film was microscopically analyzed it presented differences in thickness or in the architectural structure between different sides of the same film. This meant that the whole structure of the film wasn't homogeneous and hence didn't allow to the results of the later research to be systematic.
- **Between films.** In simple words, this meant that the thickness and structure of the film cast in a certain moment weren't the same as the ones in the film cast just before or the ones of the film that was going to be cast some time later. This type of inconsistency made for the customers very difficult to have systematic results of their research as what applied to a film may not apply to the following one.

But why did these types of inconsistencies appear? The answer to this question is very logic: as the way in which the films were cast wasn't consistent, the battery electrodes obtained as a result weren't neither. Hence, the problem was that, when the project was introduced, the films that the customers were casting were subjected to inconsistencies in their structure because of the manual casting process. This method introduced inconsistent casting speeds and stability which correlated to variability in membrane thickness. Consequently, the Werner lab required an automated device that not only assisted the customers to avoid the manual method but which also was able to reproduce homogeneous films.

Once understood that the main reason why Werner's lab needed the automated device for was to reach to the film casting consistency that they were not achieving doing the process manually, it

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was the time to ask to the clients these three important questions: 1) What is the ultimate motivation of the project? 2) Why is this project important? 3) How can this project affect a normal person's daily life? Their answer was that if by using the device that this project aimed to build they reached to the film casting regularity they wanted, the battery electrodes that they produced from then on would be able to facilitate the research on the architectural base for three dimensionally structured electrodes and batteries. This was important because these battery electrodes could have the potential to significantly decrease the charge time of personal electronic devices, increase the battery efficiency and life, and enable on-chip storage.

In conclusion, the main problem that they have is the inconsistency while manually casting and the main motivation that leads the project is building an automated device that ensures enough regularity in the later produced membranes. Only if this problem is solved, they will be able to do research on the architecture of battery's membranes.

2.2 Objectives

All the objectives that will be developed have been requested by the customer: the BU Werner Lab. As stated before, a brief was held with Prof. Werner and Anton Resing before beginning the project development. This was ultimately done to understand the objectives. The customers were seeking consistency in the casting process for research on the battery electrodes. With that in mind, from a preliminary view, the objectives can be classified into major and minor category depending on if they have to do with the high level of casting accuracy requested or not.

2.2.1 Major objectives:

- **Adjustable thickness.** The Werner Lab required the anticipated films to be cast at different thicknesses. This allows them to test different membrane's thicknesses for their battery research. In addition, testing different thicknesses showed the effects of this on a battery's durability and efficiency. The automated device had to provide cast films ranging from $100 - 600$ μm in thickness.

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- **Consistent thickness between adjustments.** The consistency of the produced membrane did not only depend on the regularity of the thickness. The customer clarified that it was not needed for the final product to cover the whole range of 100 – 600 μm in thickness, but 4 or 5 increments in between would suffice. In all of them, the most important fact was consistency. For example: If the apparatus was set by the customer to cast a film with a thickness of 200 μm, it was acceptable if the resulting membrane was 190 μm thick as long as all the membranes produced with that preset thickness were of 190 μm.

- **Constant and adjustable velocity in the casting process.** Once again, with the consistency of the produced membranes in mind, maintaining a constant velocity is vital for producing a film with a constant thickness. Not only needs the speed to be constant, but also it must be adjustable so that Prof. Werner and Anton Resing can test which of the speeds provides the most consistent membranes. Speed had to be constant and variable between 5 – 40 mm/s. It is important to consider that this is one of the objectives that has evolved through time as at the presentation of the project the stated range of variable speed was 5 – 100 mm/s. The explanation given to this change was that the customers don't manage as well in mm as they do in inches and when the 40 mm/s speed was presented to them in one of the examples it was considered as fast enough, and the objective was reset.

- **Able to hold a glass slide.** For the film casting process to be successful, the automated device must be able to hold and work with a glass slide of the following measurements: 75 x 50 x 1.5 mm (L x W x H).

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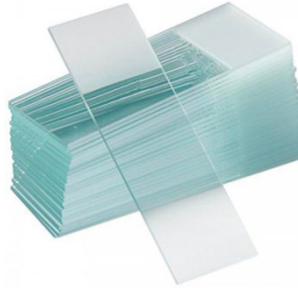
Figure 5: Glass slides used

2.2.2 Minor objectives:

- **Must account for variations in the thickness of the glass slides.** Currently, the customer's plan is to work with the glass slide's thickness stated before (1.5mm). However, if the device could operate independently of the glass slide thicknesses, it would bring more customer satisfaction. This was for two reasons: 1) In the future they might change the glass slides specifications. 2) The glass slides have imperfections and tolerances associated with them can affect the battery electrode's cross-sectional thickness. For example, imagine that the customer wants to cast a 100 μm film in a 1.5 mm thick glass slide and that the final device doesn't fulfill this requirement. If the glass slide, for any manufacture defect, ends up being 1.493 mm thick (which is a difference that the human eye can't notice) then the final film will end up being 170 μm thick (70% error). Hence, as the customers can't control the variations in the glass slide thickness, this was a minor but crucial objective to fulfill in order to be exact in the film's thickness.

- **Cleanable.** This is the least important objective. If possible, the customer wanted the device to be automatically cleanable. However, they didn't consider this to be important as the machine is always going to be supervised by the researcher and with the right materials and design, could be cleaned with no issue. Hence, the only important objective was that the device had to be manually cleanable.

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2.3 Requirements & constraints

Finally, there are some requirements and constraints that are going to be explained because they can help out to get a better idea on what is the reason behind some of the design decisions made.

2.3.1 Requirements

Although some may sound very similar to other objectives explained, it is very important to see the difference between these two. The objectives set a range of concrete engineering specifications that the device must fulfill in order to consider the objective as achieved, for example: the casting speed must be able to fluctuate between 5 – 40 mm/s. On the other hand, the requirement is only considered as an action that the device must be able to perform, following the prior example in this case the requirement would be: speed must be adjustable. In this way, the final device must…

- Be able to cast films with different preset thickness.
- Be able to hold a constant speed during the casting process.
- Account for speed adjustability following the customers' will
- Be able to stay stopped a variable amount of time after casting and before solidification. That means that the final device must allow the user to cast the film and leave it there resting for a certain amount of time (between 0 - 300 s). This is part of the precipitation process explained before.
- Perform the casting process under a 12% variation in the preset thickness.
- Be able to do a repetitive process indefinitely, always supervised by the user.
- Make sure that the dropping process of the glass slide into the nonsolvent (water) bath is in an angle that allows breaking the surface tension of the water at the same time that makes sure that the glass slide falls upright.
- Be easily moveable, that means that it must be prepared to be moved from one side of the lab to another, or from one building to another. In this way, the device must be compact to avoid breaking, and light enough so that a single person's hands can hold it (<25 kg).

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- Not need too much power. Normal wall power supplies were going to be used.

- Have a friendly user interface so that it is intuitive and comfortable for the client to use it.

- Be automatic. Careful, this doesn't mean that the device is required to work without any human interaction. In contrast, the apparatus is required to work always with the users supervision and being them the ones who decide some features of the process such as how much quantity of solution must be cast and the timing between the different steps of the process.

2.3.2 Constraints

- Limited access to the Boston University's machines. This constraint will be better understood in the following chapter (Methodology) but for now it is important to consider as a restraint that although the University had plenty resources, the access to them was limited in schedule and in availability.

- Limited time to test and acquire materials. This was due to the lead time for quotes and part procurement, and the limited window to test the final device in the laboratory as the customer required at least 5 days to take pictures of the battery electrodes. In a large and demanding project like this one every week of work is crucial and the need of having the product one week before to let the customer test it was a real constraint.

- Budget. Probably the hardest constraint of all. As it will be explained in the resources of the project, the customers wanted a product that had even more functions than the devices that can be currently found in the market. The actual difficulty comes when they ask for that but with more than 10 times less budget than the cost of these market products.

- Safety. DMSO is too corrosive to be used in the prototypes' tests without the clients' supervision. Hence, all the tests that were not supervised by the customers were always done with a product that had the same viscosity, but which was not the same as what was going to be used at the end.

- Manufacturability. This will be better developed later in the design section. However, for now it is important to state that a huge constraint was the precision of the machines that were considered as the only resources to be used. This is a project that needs plenty of rigor

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when machining, especially with the doctor blade part, and the tolerances of the Boston University's machines were a constraint.

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CHAPTER 3 - METHODOLOGY

CHAPTER 3. METHODOLOGY

3.1 Problem Approach

When asked about how the problem was going to be solved, the answer was very clear: in an iterative way. The main difficulty of the project relied on achieving a final device that fulfilled all the functions that the customers required. The technique to reach to the final device was never to work on the final prototype since the beginning of the project, but on dividing the whole project into smaller problems so that they could be solved individually and gradually.

The reason why it was thought that the project had to be attacked in an iterative way was because it was considered easier to solve each of the problems separately, always without losing the overall view of the final device the customers wanted. The idea was to start with the simpler prototype possible (a proof-of-concept prototype) and, from there, start implementing the solutions reached to every single requirement and objective that the customers had stated. Hence, every time a new prototype was reached, it had more functions implemented and the overall design was closer to the final automated device. It can be thought that using an iterative technique to solve the overall problem may have forced that once reached to a solution from a mini problem that had to be the final one. However, this didn't happen as all the prototypes were subjected to change. In addition, the customer did clearly clarify which was the objective's priority. This was considered in case of interest conflict between the solutions reached from every mini problem.

Regarding the procedures to solve the problem, there were three kinds of meetings:

- **Team meetings.** Taking the Senior Design subject in BU (ENG ME 460 and 461) had two advantages: 1) As it was a 4-credit American subject (equal to 6 European credits) it meant that in the whole year I was dedicating at least 8 credits to team meetings: 4h/week where we could discuss and put in common the individual research and work that each one of the team had done. 2) Dividing the overall problem into smaller mini problems made easy to

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split the work and hence adapt this project to the Spanish normative, where the *TFG* is individual.

- **Meetings with my project's director.** During the first semester I met weekly (short 20-minute week) with Prof. Gutiérrez-Wing so that he could supervise the progress, give his thoughts on the solutions found and give some guidance on timeline and following steps. In the second semester, these meetings were more sporadic, and the supervision was less often.

- **Meetings with the customer.** Monthly, my two teammates (Aaron and Khalid) and myself, met with the customers, Prof. Werner and Anton Resing. In those meetings, the idea was to solve whatever doubt we had about the project's objectives or how they wanted the automated device to operate. In addition, those meeting were useful to receive actual feedback from the customers on the already found solutions and design details.

3.2 Resources used

As it was explained in the context of the project (Introduction chapter), one of the main reasons why I finally chose to take part on one of the projects that Boston University was offering, instead of doing my *TFG* in ICAI or in a private company, was that Boston University has many resources to take advantage of. In addition, this gave me a huge opportunity to learn how to use resources I had never worked with or to adapt myself to other usages of the resources I already knew.

As ICAI, Boston University has many labs where students can do their own research and projects. Every lab in BU is oriented to fulfill one of the different science branches. For this project, I mainly needed access to the mechanics and electronics resources. These were found in EPIC (Engineering Product Innovation Center) and Tinker. To be able to use the machines and instruments from both labs, I had to complete two assessments. One of them was aimed to ensure safety: amendments, prohibitions, behavioral rules, safety instruments usage and emergency procedures. The second one regarded the usage of all machines and instruments, as well as introduced me to all the resources I had available.

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From the mechanical side, EPIC lab was the one that was used the most. From there, it was used: the mill, the lathe, the 3Dprinter, the laser cutter and the wire EDM. With all those machines, the device was manufactured. In addition, the software CAD program that was used to design the housing of the device is SolidWorks, which is very similar to the one we use in ICAI (SolidEdge) and which license was free as a BU student.

From the electronics side, Tinker lab had different spaces to safely work and it had many electronic components at disposal of students to implement them in their projects. In addition, it had all the instruments that were needed to solder the circuit. As it will be explained in the Electronic Design chapter, the software program used to code the electronics was Arduino. Finally, the microcontroller board that BU provided was the ArduinoUno, which was sophisticated enough to program all the features that the automated device needed.

Also, regarding the resources needed for the apparatus, an important point to be considered, especially on this project, is the budget. In this way, the economic resources are another of the advantages of doing a Boston University's project because it hasn't been me the one that has had to put the money to make the project a reality. BU could invest up to $400 on the automated device. Although this may sound as a lot, to be fair it is not compared to the options of the market that will be explained in the next chapter (State of the art). Amazon was the main company used as provider of the materials that were needed for the project.

Finally, the customers agreed on providing different kinds of resources to make sure the project was a success for their researching objectives. First, they provided glass slides samples so that the casting process could be tested when prototypes got built. In addition, as DMSO (the solvent that customers use) could be very harmful for human skin, for testing purposes customers provided samples of a liquid that wasn't harmful for human's skin but which had exactly the same viscosity. Secondly, Werner's lab offered the team extra budget in case it was needed and well justified.

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Finally, they offered specialized vacuum pumps they had in their lab in case they could be useful in the final solution of the problem.

3.3 Timeline

In the Appendix A, it can be found a detailed Gantt Chart that was made at the beginning of the year which spreads the tasks between both semesters. Of course, this program hasn't been strictly followed, but it has been helpful to constantly give an overall view on which tasks had to be done, the amount of time that was estimated for each of them and how much remaining time there was left.

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4.1 PROCESS

Before explaining what technology could be currently used to solve the consistency problem that Prof. Werner's lab faced during the film casting, it is important to understand how this process was done before building the apparatus. At the beginning of the project, it was very complicated for the lab to do research on the membranes they produced because the film casting process was done manually following these steps:

1) The thickness of the membrane was preset in the doctor blade using feeling gauges and micrometers.

2) The viscous solution (typically DMSO: Dimethyl Sulfoxide) was added to the glass slide.

3) The film casting took place using the doctor blade.

4) After casting, the film was left resting for a specified amount of time (around 1 minute).

5) The glass slide was put into water at an angle so that it broke the superficial tension of water.

6) After around 20 s inside the water, the DMSO reacted with the water and a polymeric membrane was formed.

7) The glass slide was extracted out of the water and the membrane was separated from the glass slide ready to be analyzed.
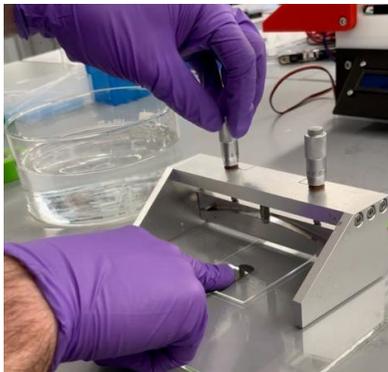
Figure 7: Presetting the thickness

Figure 6: DMSO

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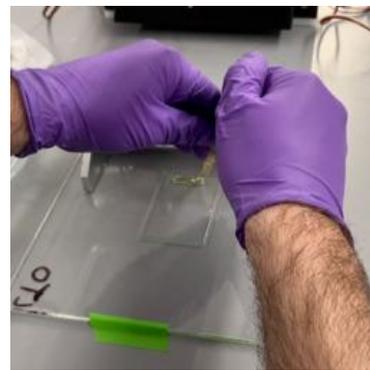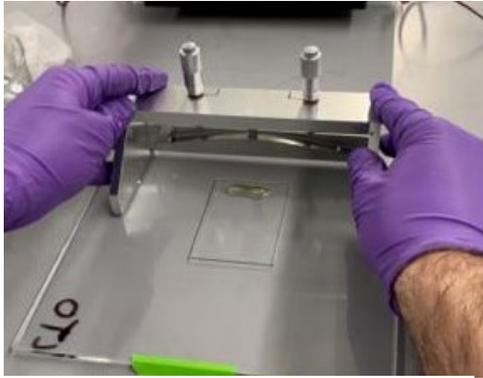
Figure 9: Casting process
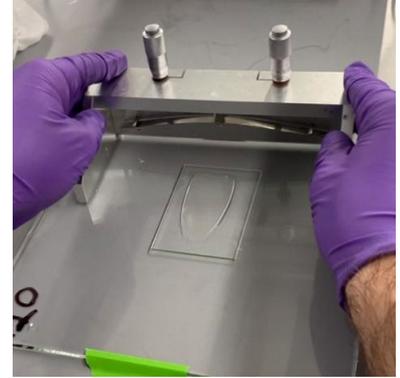
Figure 8: Resting time
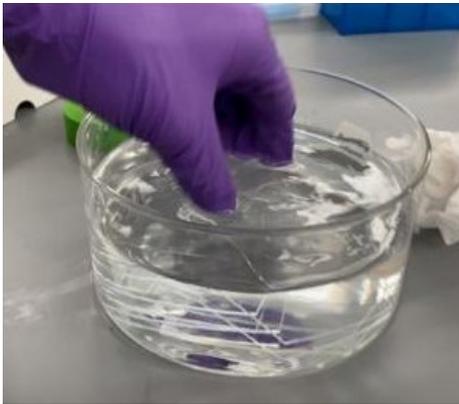
Figure 11: Water bath precipitation

Figure 10: Phase inversion process

Figure 12: Solidified membrane

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4.2 CURRENT SOLUTION

Hence, although the project objectives and functions of the apparatus have already been developed, it is important to remember that the most important physical property that had to be considered is the thickness of the film once it had been cast. This property was the one that had the most impact in the consistency of the membranes formed. Therefore, at the beginning of the project it was the property that worried the most to Anton and Prof. Werner.

Before the existence of the apparatus, to control the actual thickness of the membranes they were studying, the Werner's lab first bought what was going to be the most important piece to design of the automated device they needed: a doctor blade. It consisted of a film casting knife that had a blade width of 15.2 cm and could perform with a gap clearance of 0-3800 μm. For the thickness of the membrane to be adjustable it used highly precise micrometers to set the gap clearance. Despite they didn't use to work with such large widths, the doctor blade had a large selection of film widths. Its main material was aluminum, its weight was 0.8 kg and its dimensions were 7.6 x 16.5 x 10 cm (L x W x H). They used the blade width of 15.2 cm. However, there were plenty of different widths they could choose from when they bought it (5 cm, 10 cm, 20 cm or 30 cm width).

Figure 13: BYK instruments' doctor blade

The doctor blade they used was bought from the company *BYK Instruments*. Although it worked well, it didn't solve the problem they had due to two main reasons:

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1) The doctor blade could only be used manually and hence it didn't allow the membranes to be consistent enough within and between each other.

2) The cost of the doctor blade was $835 (excluding taxes), which greatly exceeded the budget of $400 that the costumer wanted to expense.

4.3 COMMERCIAL FILM CASTING PROCESS

As the problem aimed to solve was to reduce inconsistencies caused by manually casting phase inversion membranes by creating an automated process, it was crucial to research and understand products on the market that could already solve their problem. However, most of the time the lab equipment solutions cost well over $1000. The goal was to implement some of the features on the following commercial options while staying within the $400 budget.

Therefore, in this part of the chapter it is going to be analyzed how some key features of the process described above *(4.1 Process)* are currently solved by the existing automated machines in the market. This analysis was key in order to better understand some of the main subproblems that had to be solved while building the final apparatus:

1) **Choosing the movement reference.** In every process that involves casting, one of the most important decisions that must be taken is which of the parts is going to be in movement (moving part) and which is going to stand stopped (reference). In the market both options can be found:

   - **Moving doctor blade and have the substrate as reference:** In this case the part that moves is the blade and the glass slide stands somehow stopped while the film is cast.

   - **Moving the substrate and have doctor blade as reference:** In this case the part that moves is the glass slide and the doctor blade stands somehow stopped while the film is cast.

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2) **Fixturing the substrate.** If the design follows the path in which the substrate is the reference while the doctor blade moves, a way must be found in order to make the substrate (in this case a glass slide) stand fixtured. The market currently proposes the following options:

- **Vacuum table with vacuum hose inlet:** For example, the *byko-drive s* utilizes a vacuum inlet with holes drilled into the top surface of the table. This holds the glass slide stationary when the film is being cast.

Figure 14: Byko-drive s casting apparatus

- **Clips:** Another option would be the *Promoter MEMCAST* which uses clips behind the doctor blade to hold the glass slide to the base while the film is being cast.

Figure 15: Promoter MEMCAST apparatus

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- **Adhesion:** This is the option that was being used in the Werner Lab in September 2021, when the clients still didn't have the automated apparatus. The customers used isopropyl alcohol to adhere the glass slide to the base through cohesion.
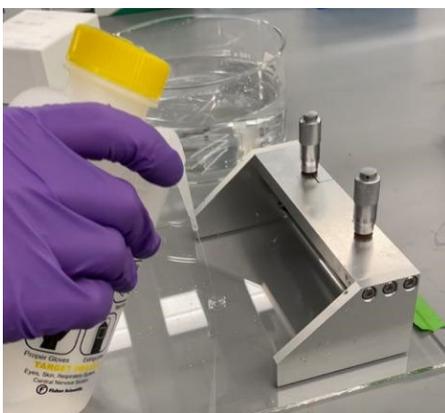
Figure 16: Adhesion method in MeMaD

3) **Solidification of the process.** All the options that can be currently found in the market solidify the membranes manually, including the method that was used in the Werner Lab at the beginning of the project. The glass slide is taken off the base and then placed into a water bath. The current commercial options likely don't automate this part of the process because they cast all types of films, not only phase inversion membranes which are the ones used exclusively in the Werner Lab.

4.4 DOCTOR BLADE

As it is the most important piece of the project, it was especially important to have on mind how this part differed between all the options that can be observed in the market. Taking this into account, the doctor blade is going to be analyzed from the following topics: shape and material.

1) **Shape.** It is important to differ this property to the one that may sound similar: appearance, as this one will be discussed in the "Adjustability" part. When talking about the shape of

the doctor blade it is key to think in the cross-sectional shape because that t is the exact part of the doctor blade that casts the film. The main different configurations that can be found in the market are the following:

- **Circular shape:** This kind of shape can be analyzed from different point of views. When referring to precision, it is true that it is a shape that totally depends not only on the precision of the machine that is being used to manufacture the doctor blade (must match the exact wanted diameter), but also on the material being used as it must be able to provide a smooth surface. However, from the manufacturing part it is much easier to machine this doctor blade's shape by only using a lathe.

Figure 17: Circular shape doctor blade

- **Square shape:** This cross-sectional shape contrasts with the circular as it can be more precise, due to the less surface considered when being machined, but also it can be more difficult to manufacture, due to the difficulty of the "corners" that must be machined. This kind is also easier to clean after being used.

Figure 18: Square shape doctor blade

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- **"Knife" shape:** It is probably the most intuitive type of blade that a person would think of when imagining this part of the project. It is also the most commercial solution that can be found as there are many projects in which these kinds of knifes are used. The perfect example of this cross-sectional shape is the doctor blade that was being used in Werner Lab before this project was assigned:
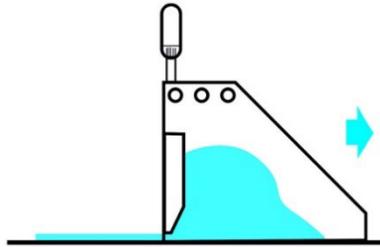
Figure 19: Knofe shape doctor blade

2) **Material.** This material analysis refers only to the casting blade. Although this section will be described more accurately in the design part of the report, for now it must be stated that there are mainly two predominant materials being used in the market:
   - **Stainless steel.** This material is preferred due to its corrosion resistance.
   - **Anodized aluminum.** This material is found in cheaper doctor blades.

4.5 ADJUSTABILITY OF THE CASTING PROCESS

This section explains the most common solutions that the different designs of the market use to solve the different adjustability requirements that the customers of the customers have asked for in their final automated apparatus:

1) **Casting thickness adjustability.** The requirement of the customers was to have a machine able to cast films between $100 - 600$ μm. In order to do so, the market proposes the following methods:

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- **Micrometers:** This process allows the client to adjust the gap that they want to have between the reference and the blade. It was the method that was being used in the Werner Lab when the process was manual. However, it was very imprecise due to the need of use of feeling gauges as the doctor blade wasn't placed in the reference (the glass slide) from the beginning.

Figure 20: Doctor blade with micrometers

- **N - sided doctor blade** (being N a positive number). It is a method that lets the user have a precise and adjustable thickness while it can be easily and quickly changed. In addition, it is adaptable to the different shapes explained before. See figures 17 and 18 (circular and square shaped four-sided doctor blades).

2) **Adjustable casting speed.** The requirement of the customers was to have a machine able to cast films at an adjustable constant speed between 5 – 40 mm/s. In order to do so, the whole market mainly uses a motor that is able to tune the casting speed.

3) **Cleanability.** Finally, one of the minor requirements of the customers was to have an apparatus that is cleanable, and if possible, easy to clean. Following this direction, the market normally makes the doctor blade easy to be removed for cleaning purposes.

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4.6 TOP BENCHMARKING CANDIDATES IN THE MARKET

There are certainly machines in the market that can be used to solve the problem, and which would ensure that the membranes have the consistency needed for the later research. However, their prices exceed by minimum of 5 times the budget constraint.

4.6.1 MICRO-scale

In the micro- scale, the two main commercial options that were found more suitable to benchmark against were the *BYKO-DRIVE S FILM APPLICATOR* and the *MSK–AFA-II-VC*. There are many more film casting options on the market, but these two reflect the global features of them all well.

In the following table it can be seen the main differences between the two selected models:

COMPARISON TABLE		
BYK INSTRUMENTS	**Brand**	MTI Corporation
Byko-drive S, G	**Model**	MSK–AFA-II-VC
470 x 356 x 203	**Dimensions (LxWxH)**	805 x 430 x 223
13.2	**Weight (kg)**	30.4
Substrate (glass slide)	**Movement reference**	Substrate (glass slide)
Clips	**Fixturing the substrate**	Vacuum chuck
Circular	**Shape**	Knife
N/A	**Material**	Stainless steel
N – sided doctor blade	**Thickness adjustability**	Micrometers
10 – 600 (adaptable)	**Thickness specifications (μm)**	10 – 5000
Motor	**Speed adjustability**	Motor
2 – 200 ± 1%	**Speed specifications (mm/s)**	5 – 100 ± 10 mm/s
Yes, but not automatically	**Cleanable?**	Yes, but not automatically
No	**Automatic immersion?**	No
4,078	**Price ($)**	4,989

Table 1: Comparison between two market options

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Figure 22:Byko Drive S G model

Figure 21: MSK–AFA-II-VC

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4.6.2 MACRO-scale

Although this is not the case of this project, if the customers were looking for a more sophisticated machine that could do the process wholesale instead of in small quantities, they could contact *Guandong Xinhuida Machinery Technology*. This company is specialized in film casting machines for big industry. Even though the quality of the resulting product would be more than enough, its prices would be between $50,000-$500,000.

Figure 23: Guandong Xinhuida machine

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It has clearly been described that the main objective of the project is to provide the customers with an automated device that can allow them to cast consistent films so that they can do later research on battery electrodes reaching to systematic results. In order to do so, there are two different designs that must be addressed, the mechanical one and the electronic one. The mechanical design will provide the device with the means needed for the project to succeed, while the electronic one will automate those means and will ensure the consistency. In this part of the memory, the design that will be developed is the mechanical one.

As it can be seen in the timeline of the project (chapter 3), some part of the first semester was used to do research on different approaches of how the project could be addressed. Most of that research was aimed in mechanical methods to make film casting a reality. This was like this because only when the mechanical decisions had been made it was going to be the time to address the electronic part of the project.

In this way, after doing the stated research on the available film casting technologies of the market (chapter 4), it is clear that this part of the design has two main topics to mainly focus on:

1. Decide on which part is going to be the static reference and which part of the apparatus is going to be in movement. Remember that it can either be the substrate (glass slide) or the doctor blade.
2. Decide on how the doctor blade is going to be designed in order to optimize the consistency of the films at the same time that fulfills all the requirements and objectives.

This chapter is going to be divided into two big sections: Preliminary Design and Optimized Design. The reason for this decision will be automatically deduced during the explanation of each of the sections.

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5.1 Preliminary Design

5.1.1 General planning

As stated before, the first two things that had to be decided in terms of the mechanical design were defining the movement and the doctor blade layout. In this section the first topic is going to be addressed. It must be remembered that in whichever casting device there must be a part that must be static (reference) and there must be a part that has to be in movement. To exemplify this with a daily life situation, it happens the same when spreading butter in a toast: you can have the toast as the reference and only move the knife or you can have the knife as the reference and move the toast instead.

In the preliminary design it was decided that the glass slide was going to be the moving part while the doctor blade was going to stay stationary. This decision was finally made after a lot of research answering to these questions: Which is the easiest part to move? And which is the easiest part to make it stay stationary? The easiest part to be moved was thought to be the glass slide as it is much lighter than the doctor blade. In addition, using the same weight logic, as the doctor blade is heavier, it was thought to be the easiest part to make it be totally static.

Now that the doctor blade has been mentioned, what was the actual plan for this key element? In the general planning at the beginning of the project the only thing that was totally decided was that the doctor blade was going to have a circular shape. It was almost compulsory to assume this due to the resources of Boston University. As stated in the previous chapter (State of the Art), the circular shape is the easiest one to manufacture and its precision is totally decent. Once explained the situation and different possibilities to the EPIC assistants they considered impossible with the available machines to have the knife shape. Regarding the square shape, although it was described as a possible chance, it was discarded because the EPIC professionals could not ensure that the square shape could be machined with the same precision as a cylinder. Hence, the square shape was discarded due to two reasons: 1) It didn't make sense to choose the square shape because of its highest precision when the assistants of the machines that were going to be used for machining

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the doctor blade could not ensure that the square shape could reach the precision of the cylinder shape. 2) The material of the doctor blade was considered since the beginning as the most expensive part of the project, and it would be senseless to expend a big part of the budget in something that is not ensured to work.

Hence, the general planning that the preliminary prototype followed is described in the following figure 24. The user would preset the process placing in the glass slide the solution and then the glass slide would start moving until reaching a constant speed. This would be followed by the actual casting process in which the doctor blade would be stationary. The process would finally end up by pushing the glass slide down through a ramp into the water bath.
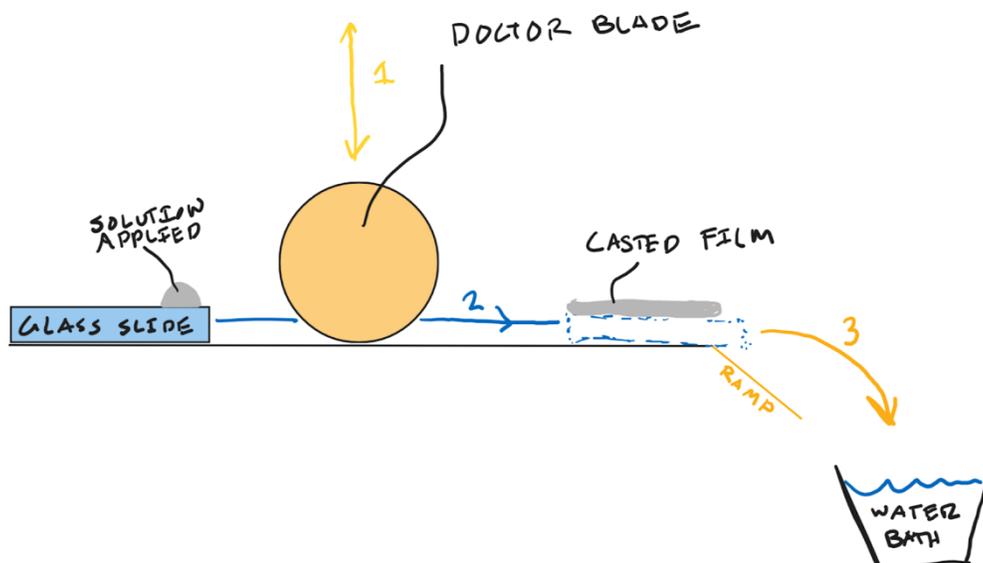
Figure 24: Preliminary design diagram

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5.1.2 Spring-loaded mechanism

Looking at the figure above it is true that the process may seem very simple, however there are still a lot of issues to address. One of them is certainly how in this preliminary design it was expected to handle the stationary state of the doctor blade and the precision required in the variety of thickness.

The problem of having the doctor blade stationary was that when the glass slide had to pass under the doctor blade in order to cast the film, it needed to push the doctor blade up. This detail was actually crucial because it meant that the doctor blade could not be as heavy as thought in the beginning in order to make it possible for the glass slide to push it upside. The immediate consequence of having a lighter doctor blade was that the surface tension of the DMSO started playing a differential role due to the high viscosity of the liquid.

In addition, two other problems appeared because of having the doctor blade stationary. The first one was that the device was not accounting for the variations in the glass slide thickness because the doctor blade could only have a method in which in order to cast a film of a prescribed thickness it would have to take for granted that the glass slide thickness is 1.5mm. The second problem was that the reference (doctor blade) and the moving part (the glass slide) had to be perfectly aligned in order to guarantee that the battery electrode was being cast exactly the same in both sides.

To solve all these problems, a single solution was reached: the doctor blade needed a spring-loaded mechanism. This meant that in the guiding slot that attached the cylindrical doctor blade to the reference (housing of the apparatus) a spring was going to be inserted. As just explained, the reason for this was triple: 1) It added an extra force to the doctor blade that together with its weight could guarantee that the DMSO's surface tension was not going to affect in the preset thickness of the films. 2) It made sure that if there were variations in the glass slide thickness the doctor blade was still going to be pushed up/down having the glass slide thickness as a reference with no matter

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which was the actual thickness of it. 3) This extra tension helped in the alignment of the doctor blade and the glass slide.

In this context, the first prototype was built. It consisted in a proof-of-concept device in order to personally test if a cylinder could work to cast a film, to test if the spring-loaded system helped solving the previously described problems and to get familiar with the project. As shown in figure 25, a relatively simple design is used to demonstrate a spring mechanism. There is a wooden pole with a spring directly attached to a 3D printed cylinder, all in a wooden case with slots on each side. The spring applies a downward force onto the cylinder that will account for variations in distinct glass slides when casting.
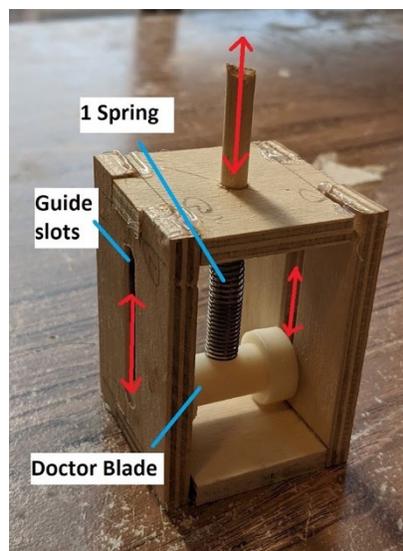
Figure 25: Detail of prototype 1

The advantages of this prototype were that it accounted for variations in the glass slide thickness and also it showed that the spring-loaded system worked. The disadvantages or improvements, however, were too many as this prototype was just a proof-of-concept.

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Essentially there were three main objectives that had to be improved for the next prototype.

- The first improvement was going to try to bring a technique to make the thickness of the cast films variable. As it can be seen in the first prototype, the 3D printed doctor blade did only account for one thickness measurement which in fact was far thicker than the ones that the customers had asked for.

- The second improvement was related with the doctor blade surface. Although it was never considered to have a final product with a 3D printed doctor blade, it was clearly experienced why. The 3D printer could not make a polish surface in the cylinder and hence its surface had thin grooves. For the next prototype the surface was intended to be metallic so that it could be as polish as possible.

- Finally, the third improvement involved stability. The cylinder showed before is fine as a proof-of concept, however, the cylinder that had to cast the films needed to have a larger carriage than this one. In this context, it was seen that a large cylinder with a single spring could lead to instabilities in which one side of the film could be cast at a different level than the other one.

To solve the problem of the long carriage cylinder and in order to make the alignment of the reference and the moving glass slide even better, it was thought that instead of having a single spring in the middle it was a better idea to have two springs, one on each guiding slot. In this way, the moment and resistance that the single spring could produce on the extreme sides of the doctor cylinder disappeared.

It is now time to introduce the second prototype that was built. In this one, it is possible to see the changes that were made to build upon the spring design from the first prototype. In particular, two springs were used on each of the ends of the cylinder, as shown in figure 26. This approach allowed for the device to be more stabilized.

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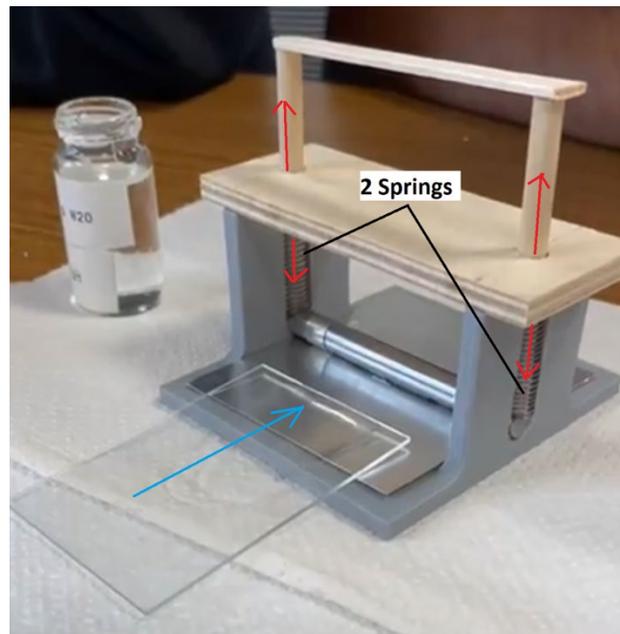
Figure 26: Detail of prototype 2

In prototype 1, glass slides with varying thickness were accounted for, with the force of the springs pushing down on the slide. In this iteration, the leveling of the surface of the glass slide and the base holding it are taken into account. If one side of the slide is higher than the other, the spring on the higher side will be stretched a lesser distance, and when the solution is finally cast under the slide, it will account for this difference. Lastly, the materials and manufacturing processes changed for the cylinder and base. In this prototype, the base was a mix of 3D printed and wooden parts. The poles and springs remained the same.

As it can be seen, stainless steel rod with metal shims was used instead of the 3D printed cylinder to simulate the doctor blade. In this way the variable thickness was implemented. In order to change the thickness of the films it was only needed to change the spacers of the sides, in this case, metal shims. Although this had as an advantage that it was a very easy and comfortable method, it also had the disadvantage that it could be imprecise as it was hard to get the correct spacing. In this way, another option of setting the variable thickness had to be explored.

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Another topic that had to be better developed was the stainless-steel cylinder. It presented two problems: 1) The glass slide could not move smoothly under it. 2) The surface of the cylinder wasn't polished enough to avoid inconsistencies. The following solutions were hence developed. 1) The diameter of the cylinder was going to be made larger. In this way, it was thought that the glass slide was going to be able to pass more smoothly under the cylinder because it won't feel like if two blocks were crashing. 2) For future doctor blades, the surface of the cylinder was going to be made with a better finish to avoid inconsistencies while casting.

In that context, this prototype still had many potential improvements. Specially, for the next prototype, the aim was to build a design in which the automated movement had already been implemented.

5.1.3 Linear and automated movement

As stated in the previous sections, although there were still many parts of the design that had to be improved, the direction that the project followed was in the line of automating the movement. This was prioritized for two reasons: 1) To check if the general design of the casting process (stationary doctor blade and glass slide in movement) made sense as an automatic device. 2) To start thinking of the electronics design of the project which was key to achieve all the customers' requirements. In this way, although the following prototype includes electronics to automate the movement, this has been left for a later explanation in the following chapter (Electronics' Design). Hence, from now on in this section and in the whole chapter, only matters that involve mechanical design will be explained but without losing the perspective that the electronics and the mechanical design are totally associated as both are crucial in the final solution.

In the next prototype a stepper motor was used to produce an automated movement at a constant speed. From the mechanical side of the project, the only clear thing was that this movement had to be linear. Therefore, the two main objectives of the new prototype were solving these two

problems: 1) How the movement was going to be transmitted from the stepper motor to the glass slide. 2) How the movement was going to be kept totally linear.

However, before solving those two problems, an important decision had to be made that was going to affect the overall design of the movement. Was it better to push or to pull the glass slide? The decision finally made was to push the glass slide, and the logic followed was the following: Both methods of movement could be implemented for a constant velocity to be easily achieved. However, a pushing method proved to be a more convenient route due to a physical space reason. Even though both methods would effectively cast the solution underneath the cylinder, the second part of the process entailed moving the glass slide off the base and into a water bath. Pulling the glass slide off the base was simply not possible given the position of the stepper motor. However, if a pushing process was used, the glass slide could simply be pushed under the cylinder and continue to move off of the base and into the water bath.

Once that decision was made, different methods were investigated to solve the two main objectives stated before. Using the movement of a normal 3D printer as a reference, it was decided that a simple but efficient way to transmit the movement was a lead screw as the one showed in figure 27.

Figure 27: Lead screw

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The challenge of using the lead screw was adapting the diameters of the stepper motor and the lead screw. The shaft diameter of the stepper motor was 5 mm while the one from the lead screw was 8 mm. In this way, a coupler lead screw as the one in figure 28 was also implemented to engage the two components:

Figure 28: Coupler lead screw

As it can be seen in the stripes of the coupler lead screw, it was flexible allowing the stepper motor and the lead screw to be at different heights without conditioning the linear movement. However, the main effort in order not to flex the lead screw was actually done by the support located in the other side of the lead screw. This support had implemented a ball bearing which allowed the circular movement of the lead screw at the same time it was being supported.

Figure 29: Ball bearing

Hence the mechanical system that allowed transmitting the movement from the stepper motor to the device followed this scheme:

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Figure 30: Movement scheme

Following with the 3D printer movement reference, the following set was bought:

Figure 31: Linear movement set

It consisted of a set of two stainless steel rods that have a polished surface allowing a linear bearing (*SC8UU* model) to slide through them maintaining hence the linear movement. In addition, the set had four supports (*SK8* model) that subjected the structure to the reference.

From the previous transmitting movement scheme, the only part that hasn't been commented is the lead screw nut (golden component) because it has been left for the following explanation on how the movement was transmitted linearly. For now, it is clear how the movement could be transmitted form the stepper to the device and how this one kept it linear, however, how did the

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movement reach the glass slide? To answer that question, two pieces were designed and 3D printed. The first one is showed in the next picture:

Figure 32: Automated movement diagram

This piece was screwed to the linear bearings and therefore, it was able to move linearly through the rods. In addition, to transmit the movement from the lead screw to the 3D printed piece, this one was screwed to the golden nut. In this way, whichever movement the stepper motor did, it was also done by the 3D printed piece at the same exact speed. Still, the movement of the glass slide hasn't been perfectly described: This 3D printed piece had the following pins that were in charge of pushing the glass slide:

Figure 33: Pushing pins

To better understand the mechanism here there is an image of the finally completed prototype in which the second 3D printed part that allowed the movement is also inserted:

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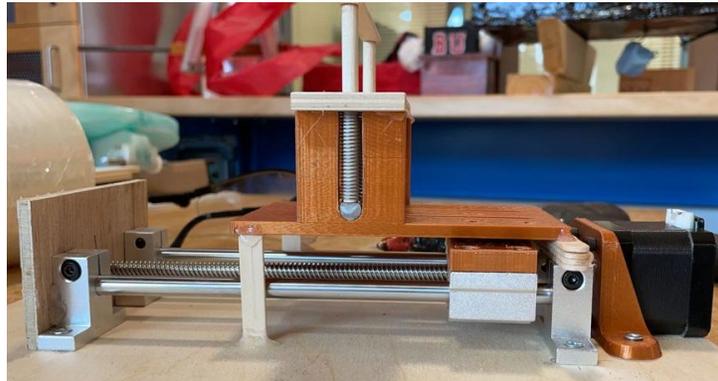
Figure 34: Side detail of prototype 3
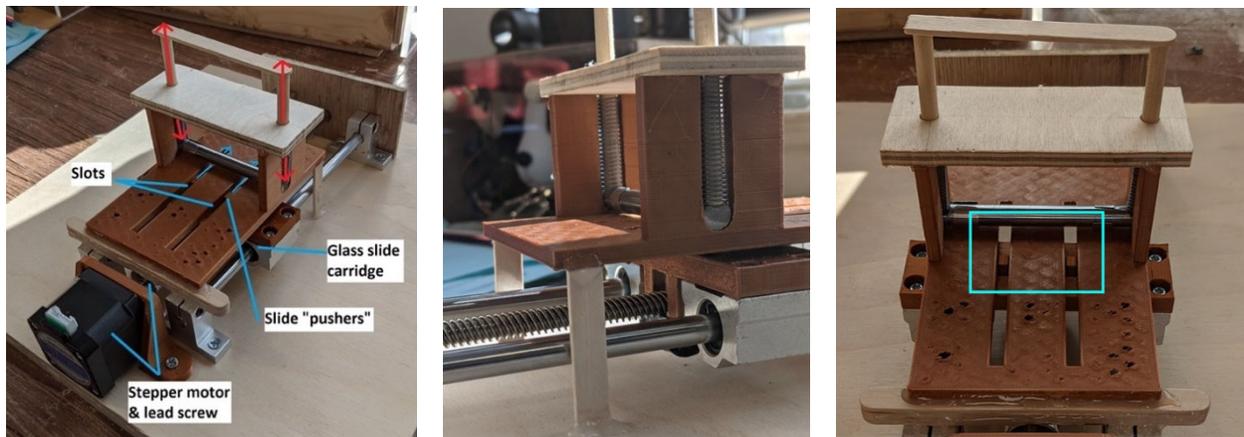
Figure 35: Front details of prototype 3

As it can be seen, through the slots the pins are able to push the glass slide and make it move at the stepper motor constant speed. In the figures, it can also be observed that what holds the lead screw is a wooden plank, this is because the ball bearings weren't introduced until the second iteration of the same prototype. As it can be appreciated, the spring-loaded mechanism is kept but there are still no changes in the doctor blade.

Although there are still too many things that needed to be improved, this third prototype was a far step to the front to set the movement standards and to take very important conclusions that will proximately be developed.

5.1.4 Design Problem

The just explained first automated iteration of the design, prototype 3, featured the stepper motor pushing the glass slide through the doctor blade using protruding pins. This design allowed for the slide to be pushed under the doctor blade, casting the film, and straight off the apparatus into a water bath in one linear motion as showed in figure 24. However, pushing the glass slide ultimately posed a number of problems:

- First, the glass slide is only 1.5 mm thick which meant that the pins that pushed the slide had to be under 1.5 mm which posed a tolerancing challenge. The reason why the pins couldn't be higher than the glass slide was that the pins had to pass under doctor blade as well and they would crash with the doctor blade.

- Secondly, the biggest problem was that the slots at the top of the assembly allowed for the casting solution (DMSO) to leak into the assembly which not only made the design not cleanable, but also would finally end up breaking the internal movement structure because it is a very corrosive solution. On top of that, the slots also weakened the top cover of the assembly making it more susceptible to snapping if it was not handled properly.

In order to try to solve the problems without changing the movement idea, another iteration of the same prototype was presented to the customers. This one, as it can be seen in figure 36, did only have a single slot to weaken less the assembly and make it more difficult for the DMSO to leak inside the structure. However, they rejected this version because it didn't really solve the two problems just stated.
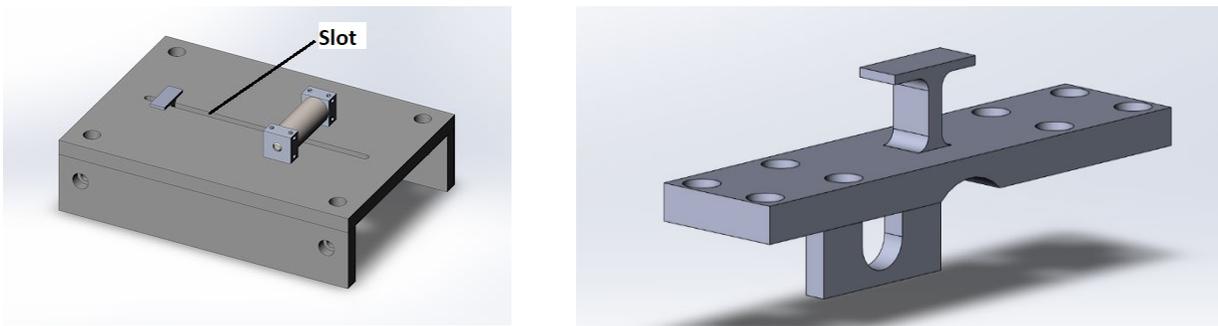
Figure 36: Detail of the second iteration of prototype 3

5.2 Optimized Design

5.2.1 Solution

Once the first idea of design wasn't a total success and it was clear that it did not meet the customers' expectations a new, it was needed a process in which every step taken until then had to be questioned. Therefore, this process of rethinking the whole apparatus lead to a situation in which none part of the design was essential and in which none already made decision was fixed. In this way, it was decided to go back to one of the main decisions of the mechanical design of the device that was described in the introduction of the chapter: Which part of the movement was going to be stationary, and which one was going to be in movement. In the previous design, the doctor blade was stationary, and the moving part was the glass slide. However, this was about to change. For this new optimized design, the glass slide was going to stay stationary while the doctor blade was going to be moving.

This certainly could save some of the problems that the design was having such as: cleanability, the problem of the DMSO leaking into the structure or the need of having a lighter doctor blade because the glass slide had to be able to push it up. This last problem saved other subproblems such as the surface tension (with a heavier doctor blade this wasn't going to be a problem anymore), the need of a spring-loaded mechanism and the stability issue.

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However, this decision also brought some questions back to the table such as:

1) How the doctor blade was going to be moved.

2) How was the glass slide going to stand stationary during the casting process.

3) Which system could be used in order to make the glass slide fall into the precipitation bath.

In this way, to solve the problem of the DMSO leaking into the slot as well as weakening the top piece of the assembly, this one was removed completely. As a result, the casting procedure was changed to an overhead design like in most commercial options like the *byko-drive S* seen in figure 22. But from then on, how was the doctor blade going to be moved? Instead of moving it with an internal pin, which was demonstrated to be an error due to the slot that provokes in the design, an external structure was going to be tested. In this context, a new component called the push bar had to be developed so that the doctor blade could be pushed but this time thanks to an external piece. This overhead design was going to allow for the assembly to be cleanable because the doctor blade and push bar were going to be designed with the ability of being removed for cleaning.

For the second question on how the glass slide was going to stay stationary many different methods were considered taking as a reference the commercial ones explained in chapter 4 (State of the Art). However, from the different methods suggested to the customers the one that most convinced them due to its simplicity was milling down a lip in the top cover of the assembly to make it work as a wall preventing the glass slide from moving. This solution, however, involved two considerations:

1) The doctor blade had to start the process on top of the glass slide in order not to be kept stopped for the exact same lip. This could create a problem with the constant speed due to the small space of acceleration, however, this problem is treated in the next chapter (Electronics Design). In addition, this was seen as an advantage because if the doctor blade started on top of the glass slide, then the objective of accounting for glass slide thickness' variations was already achieved.

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2) The push bar had to operate from a higher level than the reference to push the doctor blade without pushing the glass slide.

Finally, the third main problem of this new design was how to make the glass slide fall into the precipitation bath. The new lip just introduced in the solution of the second challenge made this problem even worse because this "wall" didn't allow moving the glass slide forward, just backwards. Hence, the movement of the device had to be in two directions. The first one was going to be the casting direction (forward) while the opposite one (backwards) was going to be the direction in which the glass slide was going to be dropped into the water bath. To facilitate the dropping part, a ramp was going to be included in the design. This system had three main advantages:

1) The doctor blade wasn't in risk of falling into the water bath as it was going to be moving in the opposite direction.

2) The need of changing the direction of the motor made easy for the electronics side to reach to the objective of letting the user choose the amount of time between the casting process and the precipitation of the glass slide into the water bath.

3) It was the perfect design for the doctor blade that was being designed in that exact moment which is proximately going to be developed.

Below, it can be seen a diagram of the optimized film casting process so that it can be perfectly understood:

4. The glass slide is kept stationary by using a milled down lip in the top cover of the assembly and the solution is applied onto the slide.

5. The doctor blade is placed on the glass slide (at a prescribed thickness) against the push bar and advances linearly casting the film.

6. A 'plow' mechanism (shown in orange) is then deployed and the push bar is reversed, leaving the doctor blade behind. The plow then pushes the glass slide off into a water bath to solidify the film.

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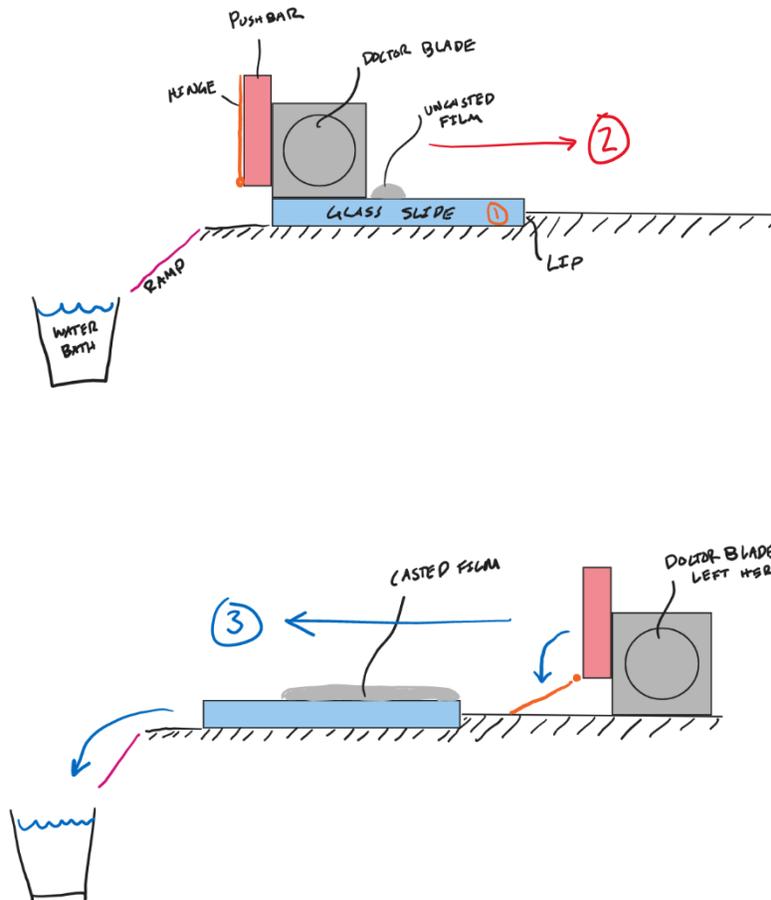
Figure 37: Diagram of the optimized design

Now that the optimized idea of the casting process has been described, it is time to show how the different components that made it possible were designed: the push bar, the lip, the hinge and the ramp.

- **Push bar.** As explained before, to move the doctor blade across a glass slide, a 3D printed push bar was used. This push bar was attached directly to the stepper motor, thanks to the same moving system that was described in 5.1.3 Linear and automated

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movement, which had been designed before also for prototype 3. In the final design of this push bar, the push bar could complete two functions: 1) Push the doctor blade at a a constant speed during the casting process, and 2) Be dropped to a lower position (thanks to the hinge) to push the glass slide off the device and into the water bath.
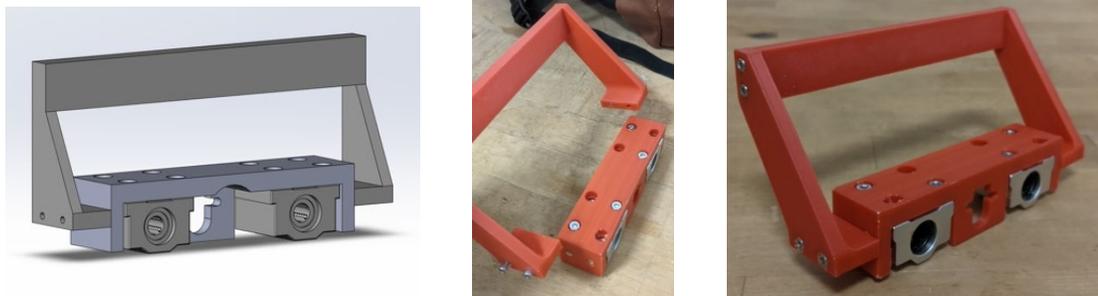
Figure 38: Detail of the push bar design
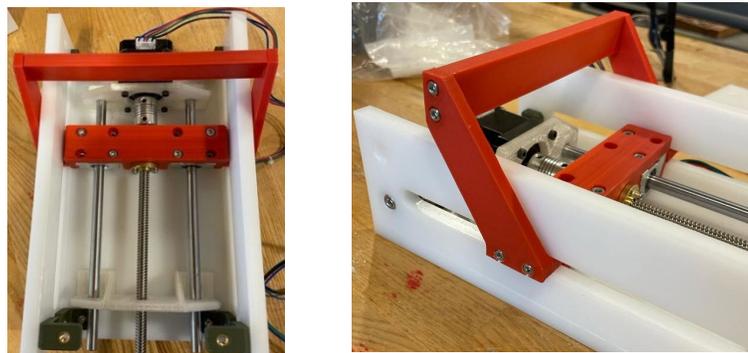
Figure 39: Detail of the assembled push bar

- **Lip.** It simply consisted of having two different levels on the top cover of the apparatus. The lower one was the glass slide level, that is where the substrate was going to be stationary thanks to the "wall" (lip) to which it was embedded.

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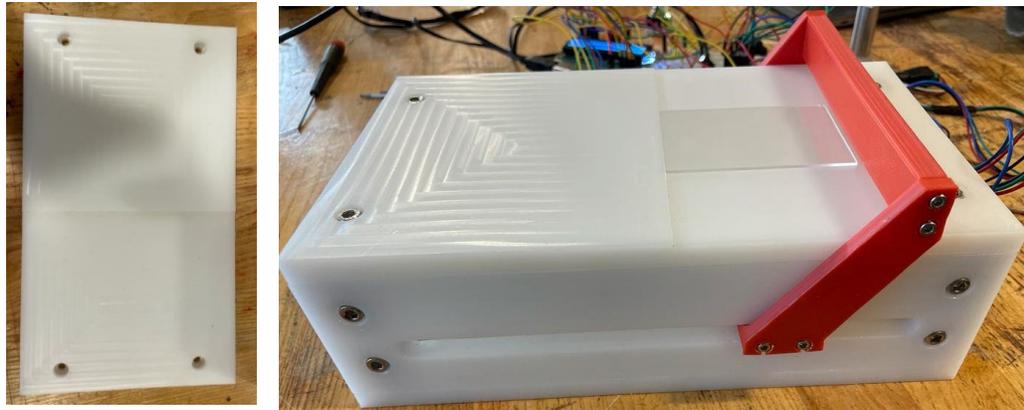
Figure 40: Lip's detail

- **Hinges.** The design finally used was different from the one explained in the optimized casting process. It had two iterations. The first one was 3D printed:
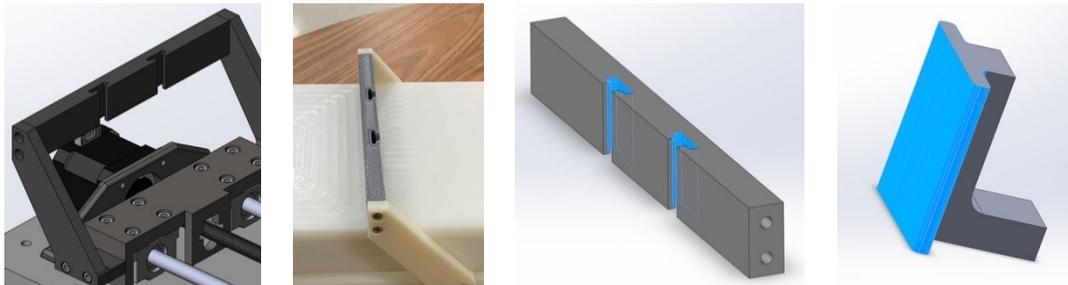
Figure 41: Hinges' first design detail

However, this design did not work as stated because the friction of the pieces was not good enough in order to fall in the exact moment in which the casting process finished, that is when the doctor blade leaves the top of the glass slide and the new reference starts being the upper level of the top cover. Often, the pieces, or sometimes only one of them, stayed stuck in the cavities and hence it was impossible to ensure the customers repeteability. That is why this second iteration was designed: A metalic push bar in which two holes were made using the CNC milling machine. This time the pieces were two small metalic cylindres.

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Figure 42: Final hinges' design

- **Ramp.** It was an additional piece that could be screwed to the main body of the apparatus. It consisted of a 3D printed slide that had its main surface polished to facilitate the slide off of the doctor blade.
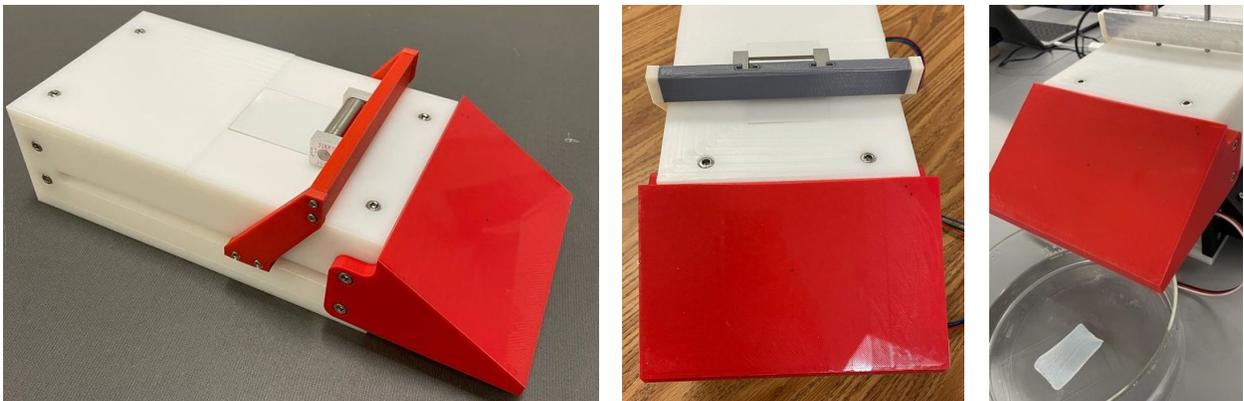
Figure 43: Ramp's design

5.2.2 Doctor Blade & Tolerances

Now it is going to be developed how the most important part of the project was finally designed in the optimized design of the apparatus. For that reason, it is important to remind the main decision that has been explained at the beginning of the chapter: the doctor blade of this project was going to have a circular casting surface, and hence, it was sure that the doctor blade was going to be a cylinder (due to the manufacturing advantages already explained). However, the doctor blade has suffered two important iterations: one in the preliminary design and the second one in the optimized design.

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In the preliminary design, it has been explained that the plan was to have in a spring-loaded position. In this design iteration, a glass slide was expected to pass under the doctor blade and be cast to a prescribed thickness. In order to set that prescribed thickness, the doctor blade featured circular shims. In this design, it was expected for the shims to be switched to change the thickness of the designated cast film. See figure 26.

However, it has already explained that the design had to change in order to reach to the consistency needed by the customers. In this way, consulting them, it was decided that the four-sided doctor (see again explanation of section 4.5 Adjustability) blade was the easiest method to ensure: 1) A variable thickness 2) A cleanable surface 3) Consistency and precision between thickness adjustments. The four thickness' ranges chosen by the customer were: 100, 200, 400 and 600 μm.

In this way, the first idea was to buy a piece of stainless steel and machine the doctor blade in Boston University's labs. However, in EPIC micron tolerances were unachievable and required specialized equipment. The best tolerance that could be achieved in the specialized milling/turning machine of EPIC was ± 0.001'' which equals ± 25 μm. Even though this is totally a really good precision for a lab university machine, the precision was not good for the original plan of turning down the whole doctor blade in EPIC. If the doctor blade had been machined there, in the worst case scenario it could have resulted in a 50% error in the 100 μm thickness and a rough surface finish. After consulting with the customers, this was considered unacceptable.

As a result, the design changed to be 3 different pieces, the cylinder and two squared aluminum blocks. The design still consisted of a 4-sided doctor blade composed by an off-centered steel cylinder press fit between the two blocks, with holes using the wire EDM machine of EPIC. As described previously, this design allowed for a specified thickness to be changed both consistently and quickly, as opposed to other adjustments such as micrometers, or the shims.

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It was decided to purchase a tight tolerance stainless steel rod (from the company McMaster) with a diametral tolerance of $\pm$ 0.0005'', which equals $\pm$ 12.7 μm, that had a polished surface. This tolerance would correlate a ~26% maximum error in the 100 μm thickness, ~ 13% in the 200 μm, ~ 6.5% in the 400 μm and ~ 3.5% maximum error in the 600 μm configuration. After consulting again with the costumers, this was accepted, and the consistency objective was totally interiorized. They explained that the 100 – 600 μm layer thicknesses were a bit arbitrary as long as the gap width throughout the blade was constant and there was a noticeable difference between the preset thicknesses. On top of that, it was discovered that the cast thickness was not exactly the same as the thickness of the battery electrode once that it was solidified after the precipitation process and, therefore, it was not extremely crucial if the thickness was not exactly 100 or 200 μm, as long as it was a $\pm$ 13% or $\pm$ 6.5% difference respectively, considered both small and acceptable deviations. The following figure describes the just stated thickness difference in the battery electrodes before and after they pass through the precipitation process, the image has been taken using the SEM (Scanning Electron Microscope) technology that the customers have access to and it shows the battery electrodes' architecture after being cast.

Cast Height: 175um
Membrane Thickness: 48um

Cast Height: 250um
Membrane Thickness: 96um

Cast Height: 330um
Membrane Thickness: 156um
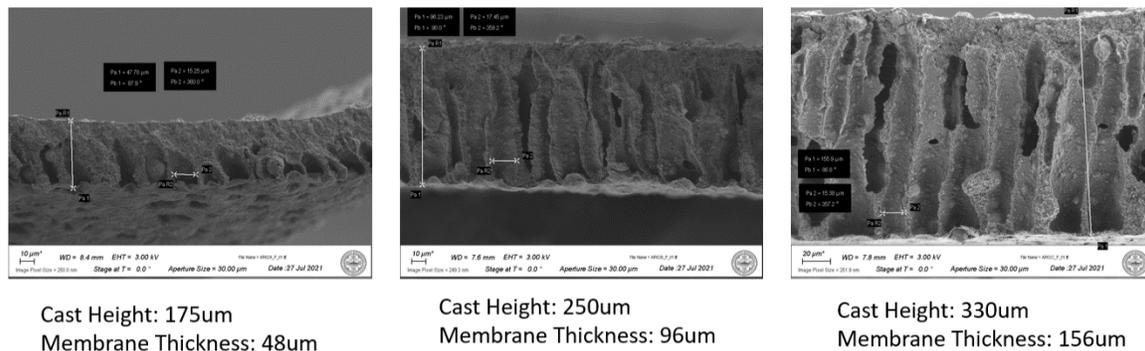
Figure 44: SEM detail of past cast membranes

The CAD sketches designed for the doctor blade is shown in the following figures. It was adapted to make use of the tight tolerance rod, as shown below. In addition, it was going to use accurate locational fits for the spacer blocks, which were going to be machined out of aluminum:

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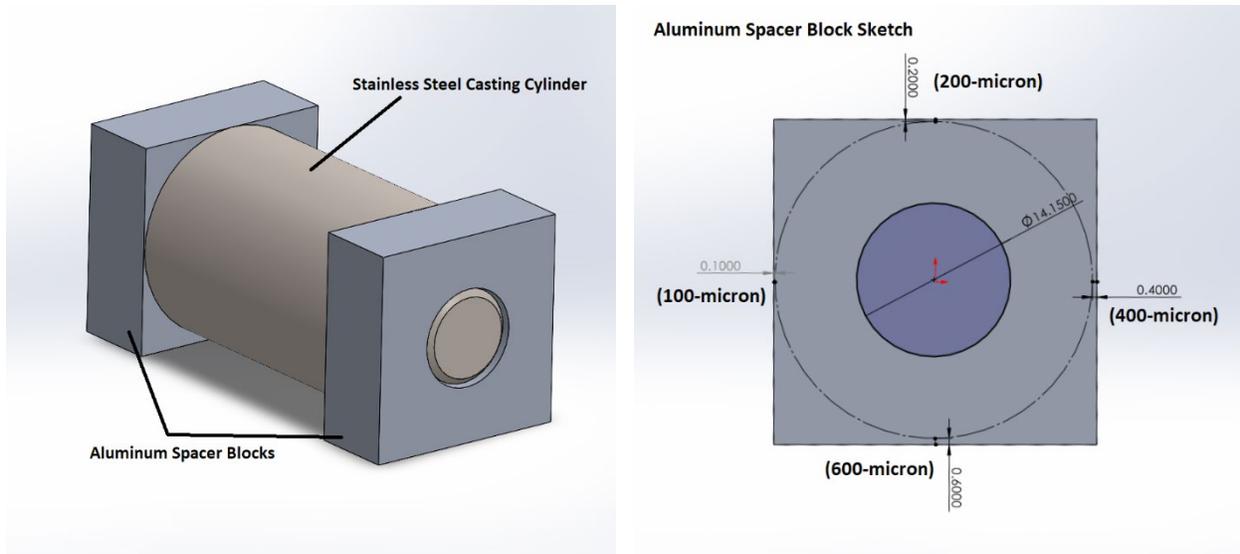
Figure 45: Doctor blade's CAD design

The important thing of the sketch is in the narrowed down dimensions of the borders of the cylinders because those are the ones that demonstrate that the cylinder was off-centered to allow it to cast films with different thicknesses (which are almost impossible to perceive with the human eye). To see the detail of the design the CAD sketches of the doctor blade have been attached in Appendix B and Appendix C.

Once this had been designed, there was a final challenge regarding the manufacturing of the doctor blade which was getting the locational clearance hole to be accurate enough on the shat and hole so that it was the same on both ends of the rod. If this wasn't achieved properly, then one side of the doctor blade would have at a different gap width that the other and it would have correlated to a sloped cross-section in the film.

As the holes and the joining was going to be done as perfectly as possible, the only way to know if it had been done successfully was through the imaging equipment from the Werner lab. The specialized microscopes, with the SEM technology stated before, could take images of the cross-sections and then be later analyzed using software to measure the exact distance (thickness in

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micron resolution) of the cast battery electrodes of the test. Therefore, through imaging the blade and samples it could be determined the accuracy of the blade and the manufacturing process could be evaluated from there.
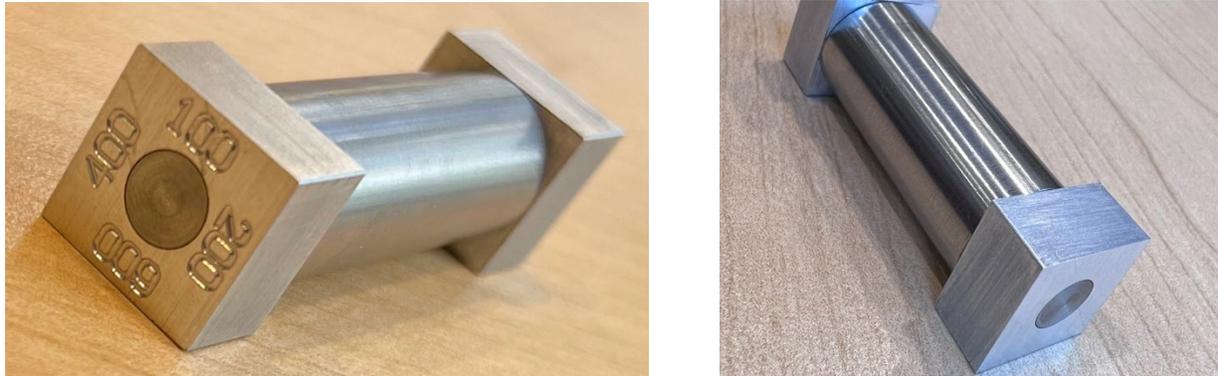
Figure 46: Manufactured doctor blade

In comparison with the rest of the elements of the apparatus, the doctor blade looked like this:
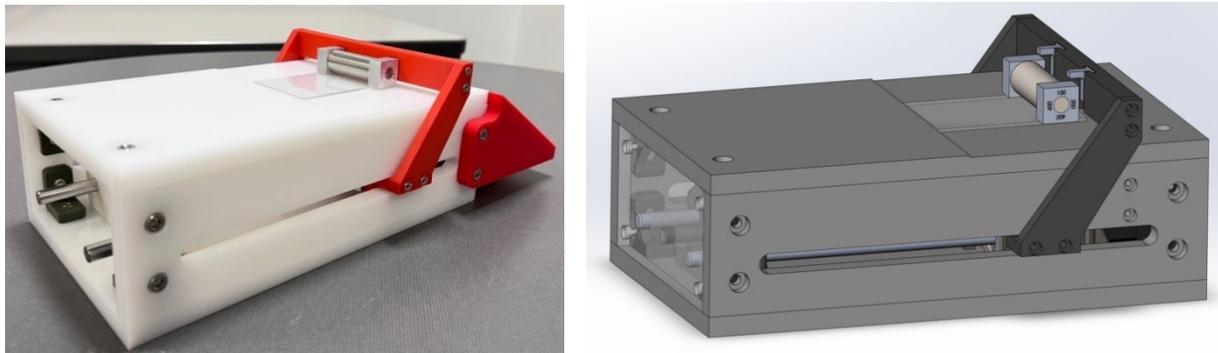
Figure 47: Doctor blade with the assembly

5.2.3   Mechanical Housing

As the sides and structure of the housing were not designed by me (but by Aaron Pan and Khalid Isahak), they have not been added to this memory.

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5.2.4 Materials

HDPE (high-density polyethylene) was the choice of material for the film casting housing due to its good chemical resistance, low moisture absorption, and fair price. HDPE is non-polar which makes it resistant to many different chemicals. In addition, since HDPE had low moisture absorptivity if any chemicals were to spill (such as DMSO), they would have a low chance of absorbing into the plastic. For this use case, DMSO was chemically compatible with HDPE, meaning it would have not reacted with it, so it was a safe choice. In terms of manufacturability, HDPE was a low-cost and easy-to-machine material, thus it was chosen.

Figure 48: Detail of the housing being machined

The extreme side pieces of the housing, used to cover the electronics (which will be later described) and mechanical components, were made from PP (polypropylene) due to its transparency to see the components as well as its chemical resistance.

Polycarbonate and Acrylic were also considered. However, polycarbonate was omitted due to it being reactive to DMSO. Acrylic was also left out due to its poor surface finish after machining which would get scratched. Teflon would be the ideal choice due to its non-polar nature, very good chemical resistance, and easy machinability. However, a sheet of Teflon would cost ~$100, almost a quarter of the budget, to get a sheet suitable for the casting top surface.

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The mechanical side of the project is key in order to design the main structure of the apparatus and to study the different ways that can be followed to achieve the consistency needed by the customers when casting the battery electrodes. It can be said that the mechanical side of the project provides all the means needed to succeed in the project. However, this success doesn't only depend on the means, but also on the functions that the resulting machine can perform. This is exactly the reason why this chapter is fundamental. As stated in the title of the project (Automated Membrane Casting Apparatus for Novel Energy Storage Architectures), the result must be an automatic device that is able to perform a phase inversion process without a direct intervention of the researcher, only his supervision. In this context, this chapter will analyze all the electronics development necessary to automate the apparatus and its cohesion with the mechanical side.

6.1 Requirements and Design

In this section of the chapter, it will be analyzed those functions of the apparatus that needed electronics solutions in order to be performed and how each of them was thought to be achieved. As in the mechanical side of the project, in the process of designing solutions for the automatization requirements, there have sometimes been different iterations until a solution was reached which was considered as optimal by the customers and which fulfilled the consistency required by the battery electrodes that have to be cast.

The electronics requirements can be classified in the following way depending on the final objective they pursue:

6.1.1 RESULTS' requirements

These requirements follow the target of enabling the user to reach to the maximum level of consistency possible when casting the battery electrodes. Embracing these needs was key for the machine to cast homogeneous membranes that could lead up to systematic results in the customers' later research. These requirements are:

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1) **Linear motion at a constant speed.** Maintaining a linear movement at a constant velocity is vital for producing a film with a constant thickness. Hence, this requirement is key to provide the within-sample consistency that was described in the Motivation chapter. A clear example that describes why preserving the constant speed for the entirety of the actual casting process is imperative would be if, for instance, the film was cast at an increasing velocity, it would have the potential to be pocketed with air bubbles and overall inconsistent thicknesses. A sudden surge in the speed of the doctor blade while casting could obstruct the already cast solution, resulting in an unusable battery electrode.

Since the early beginning of the project the customers expressed his will of having a motor to provide the mechanical movement of the apparatus. As this movement had to be linear and at a constant speed it was decided that the best way to achieve that was to use a stepper motor, which provides linear motion and can provide a constant velocity if it receives a constant current. As explained from a mechanical view in the past chapter, this device allowed for a simple, yet effective, way to use a push bar to move the doctor blade across the glass slide and then move the glass in the opposite direction into the water bath.

The chosen stepper motor was the *Nema 17* (*17HS15-1504S-X1* model) which had the specifications attached in Appendix D. The most important specifications that lead the choice of this model were the fact that it was bipolar (very important to provide movement in both directions), it could hold a torque of 45 Ncm (more than enough knowing that it would only need to face a friction torque of less than 1 Ncm), it had a decent weight (280g), and perfect dimensions (L x W x H: 39 x 42 x 42). There were no iterations concerning the stepper motor to use in the device as the first choice was made with enough criteria and its performance was excellent during the whole development of the project.

Figure 49: Stepper motor

A final comment regarding the constant velocity: It is true that ones the device reaches a constant speed the stepper motor will keep it constant until the end of the casting process. However, what happens during the slot of time in which the motor passes from a stopped state to the constant speed state? Isn't it accelerating? Yes, it is obviously true that until reaching the final constant speed the motor has to accelerate. However, this speed-up slot doesn't affect the result of the battery electrodes as it has been checked in the resulting membranes that, in the worst case scenario (40mm/s), the stepper motor has already reached its constant speed in the existing distance between the initial position of the doctor blade and the solution ~10 mm.

2) **Smooth movement.** Another requirement very important for the customers was that the movement had to be smooth enough to avoid any kind of irregularities in the surface of the cast battery electrodes.

Before deepening into that requirement, it is very important to present another component of the circuit which is the actual interface between the controller (Arduino) and the stepper motor: this component is the motor driver. This electronic piece has the capability of handling the low currents and voltage that the Arduino is able to provide as signals and turning them into the higher currents and voltage that the stepper motor needs to work as expected.

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The first motor driver used was the L298N H-Bridge which used an electronic circuit that switched the polarity of the voltage applied to the motor. In this way, the motor driver was able to change the turning direction of the motor by changing the polarity of the voltage applied to the motor. The reason why this kind of circuit has this name is the physical shape of the circuit, which looks like the letter "H" (see figure 49). The four switches represent the branches of the letter, while the load (in this case the motor) represents the cross-bar.
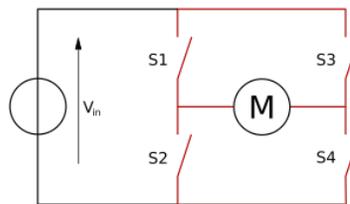
Figure 50: H-bridge motor driver

The reason why this motor driver was the first one to be implemented in the apparatus was because it easily gave the user the actual capability of changing the direction of the motor using a very simple code. When it had to go forward, the driver only had to be set with switches 1 and 4 (S1 & S4) closed and switches 2 and 3 open (S2 & S3). However, if the motor was wanted to go backward, it was only needed to change the switches' configuration by leaving S1 and S4 open, and closing S2 and S3. Both states are represented in the following figure:
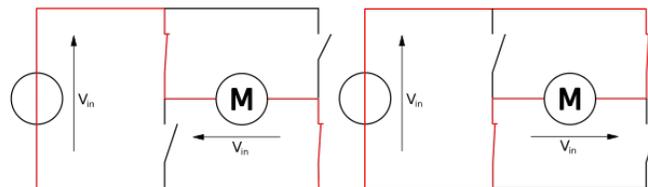
Figure 51: H-bridge different directions

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A limitation of this motor driver was that it did not work well at the low speeds that the customers wanted (5 – 40 mm/s) because it introduced lots of vibration. In this context, it is important to first understand how the stepper motor described in the previous requirement works: The *Nema 17* has a step angle of 1.8 degrees, which means that it completes an entire revolution in 200 steps (360/1.8). This leads up to 200 different positions in which the motor can stop in. Although 200 steps per revolution sounds like a number that could make the movement very smooth, in fact it wasn't enough. The movement was too steppy when performing at low speeds and it also made the apparatus very noisy, leading to inconvenient results.

To solve this problem, it was taken as a reference a classic 3D printer which uses the same type of motor but includes a novel capability in its motor driver called microstepping. This means to divide each of the 200 steps into smaller steps (called microsteps) creating very fine steps revolutions. The idea was to benefit from this technique to produce a smoother movement as many other applications benefit from it. For instance, 3D printers, which gain the capability to produce finer features and smoother surfaces. Hence, it was found that a micro-stepping driver was needed to fulfill the customer's requirement of regulating speed between 5-35 mm/s.
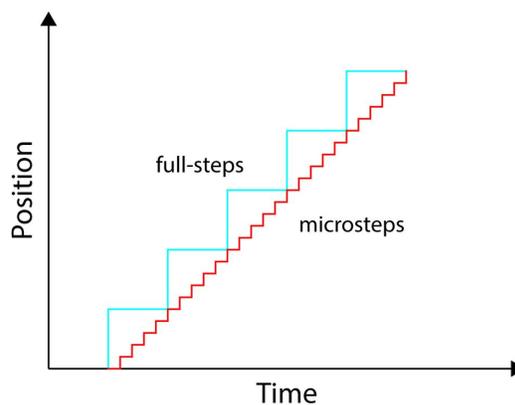
Figure 52: Microstepping

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As a result, the final motor driver that was tested was the A4988 motor driver. It consists of a micro-stepping driver that can control the bipolar stepper motor used in this project. Only two digital pins are needed to control the whole motor: one pin to choose the motor direction and the other one to choose its steps. Unlike the previously mentioned H-bridge motor driver, the A4988 is able to provide five different steps resolutions: full-step, half-step, quarter-step, eight-step, and sixteenth step. Hence, it can divide each of the previously mentioned 200 steps into 16 microsteps meaning on 3800 steps to complete a revolution. The result was very positive as it did not only lead up to smoother cast membranes when using lower speeds, but also made the machine quite less noisy.
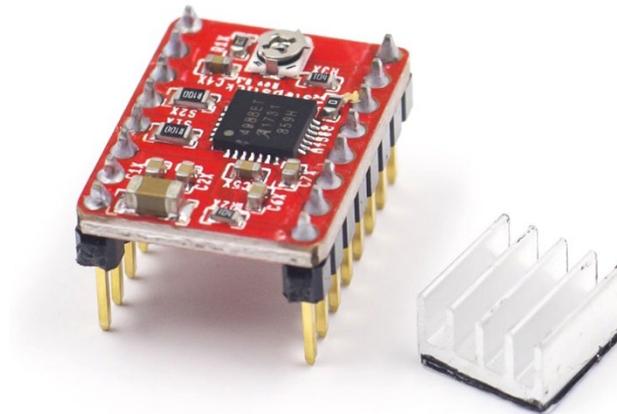
Figure 53: A4988 motor driver

As it can be seen in the image above, the A4988 usually comes accompanied with a heatsink to avoid overheating.

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3) **Variable and adjustable speed.** Although this requirement doesn't aim exclusively to achieve the maximum level of homogeneity when casting the battery electrodes, it is a key one for the customers to do their later studies on the membranes they cast and to be able to check which casting speed provides the best results. A potentiometer was used in order to provide the customers with an apparatus in which they could regulate the casting speed.

The first potentiometer used in the project in order to make the speed variable was the *T103*. It consists of a three-terminal element that is able to provide a variable resistance up to 10kΩ. This model of potentiometer is the simplest of the market, it has three pins that are connected directly to the breadboard. Using an adjustable 270 degrees rotation, the potentiometer sets the resistance and hence sets the signal that is transmitted to the Arduino, which will then read it and use it to set the respective speed.

Figure 54: Potentiometer T103 10kΩ

Disadvantage: There were two issues regarding the use of this potentiometer: 1) Although it was useful to test if it was going to work regulating the motor's speed, in real life it was too small and inconvenient for the customer to work daily with it once the apparatus was built. 2) It was a bad quality potentiometer. This fact was good at the beginning because it was cheap to test its use. However, its quality was too bad to last as long as the customer wanted without leading to precision errors because of mechanical issues.

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Hence, the second and final potentiometer used was the RV24IN 20S/B103. The result turned out to be very successful because it solved the problems that the previous one presented: It was much more convenient for daily use and much more precise. In addition, its design made easy to solder the wires and avoid future connection problems.

Figure 55: Potentiometer RV24IN 20S/B103

6.1.2   USER INTERFACE requirements

These requirements not only follow the target of providing the apparatus with all the electronic means needed to perform its functions properly, but also providing the customers with an intuitive manner to use it. These requirements are:

1) **Speed configuration.** Once designed a way to make the speed variable, how can the user know which speed has been chosen or which speed options there are? The answer to these questions is that there is a clear need to have an interface between the user and the apparatus to actually control the casting speed. In the project, this bond was achieved with an LCD Display.

   The Liquid Crystal Display used in the project is a common component in the electronic devices as it gives the capacity to the microcontroller to write information into it and hence, communicate something to the user. In this case, the information to be communicated was double: 1) The state of the machine (Stopped, backward or forward) and 2) The speed being

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selected (from 5 - 40 mm/s). The LCD used for the apparatus was from the brand *HiLetgo*, its screen size was 1'' and it could display up to 2 lines of 16 characters each. It wasn't needed to iterate as it fulfilled its function perfectly since day 1.

Figure 56: LCD display

2) **Direction of the motion choice.** In the description of the process that the final apparatus must perform it has been explained how the device must cast the solution and drop the glass slide into the precipitation bath in an automatic way. However, it has also been appointed that automatic doesn't mean without supervision. In this line, the customers are expected to be the ones that follow up the casting process and make the decisions of when and how must every step of the process be completed.

In this context, the intention of the user must be able to be communicated somehow to the machine and this one must be ready to read that signal, process it and respond with the correspondent action. The main three actions that the apparatus was expected to "ask" to the user when performing the casting process are: 1) "*At which speed do you want to cast the solution?*", 2) "*When do you want to start casting the solution?*" and 3) "*When do you want to drop the substrate to the precipitation bath?*". The electronic process that answers to the first question has already been explained in the previous segment. However, the answer to the second and third questions hasn't yet been developed. The solution is simple and intuitive: the best way to turn on a movement is a push button. Therefore, as there are

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two motions possible: 1) Casting movement (in this case anticlockwise movement of the stepper motor) and 2) Precipitation bath movement (in this case clockwise), two buttons were used, one corresponding to each of the movements.

From a design view, the *QTEATAK* push button was the type of button used at first place and the one that was implemented in all the prototypes from December to April. These are the simplest buttons of the marked and worked very well. The main issue that they presented was strictly mechanical: The user pushed the button once, but the Arduino read it as if the push button had been pushed 10 times. This issue was easily solved adding a delay of 50ms in the code.

Figure 57: Push button QTEATAK

Disadvantage: It was agreed with the customers that their size was too small (6x6 mm) to make the use of the apparatus comfortable enough. Hence, in the implementation of the electronics housing these push buttons were changed by bigger ones with which the customer felt more comfortable working with and which tend to be more durable.

In the image below it can be seen the push button finally used, which accounts for the size disadvantage stated before. The push buttons have a diameter of 1 cm which makes daily use much more convenient. In addition, this type of push button has two important advantages: 1) They are made to be soldered, which didn't allow any type of false contact between the wires. 2) The design was perfect to remain screwed in the electronics box that will be described later.

*Figure 58: Panel Mount
momentary push button*

3) **Ability to stop the apparatus at any time.** As in almost any kind of automatic device that performs a dangerous process or which works with dangerous materials, the customers of the project asked to have a way to stop the machine whenever they wanted. This was an important requirement as the solutions that they usually work with tend to be very corrosive. In this context, if there was a solution leak (for instance DMSO) in a place that could carry to even worse consequences or if there was a mechanical breakdown that could damage the whole apparatus housing, the user would need an easy way to immediately stop the activity of the device.

The most common and intuitive way seen in the market in all kinds of machines is using a button that can immediately stop the device at any time. Although the iteration of buttons is not going to be developed again as it is the same one as in the previous requirement, it is interesting to point out that for customers' demand this button had to be red.

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4) **Bounded movement.** The motion of the mechanical parts that cast the films has already been described from all its point of views: linearity, velocity, smoothness, variability, activation, and emergency deactivation. However, what about how to stop the movement of the push bar in the standard use of the machine? The answer to this question is key for two main reasons: 1) As stated before there are two linear movements that summarize the use of the machine, the one for casting (forward) and the one that takes the substrate to the precipitation bath (backward): once each of these motions has already completed its objective (casting and dropping respectively) there must be a way to tell the machine that this has already happened and that the stepper motor should stop. 2) It is also important because if there wasn't an immediate stop of the device when these objectives have already been achieved then the device would finally end up having a mechanical breakdown as the motor would keep trying to move the push bar where there isn't physical space to do it.

Hence, once understood the reason why having a bounded movement is so important it comes the moment to discuss which different approaches have been followed to fulfill this requirement. In first place, it was thought that the best way was using the stop button described in the previous requirement. Nonetheless, this way was early rejected as it was found very inconvenient because it required a lot of user interaction and questioned the full automatization of the apparatus.

Thus, one more time the project took inspiration on the classic 3D printers and a very efficient electronic component was found to fulfill this requirement: a limit switch. It consists of a mechanical endstop from the brand *GUBCUB* that has 3 pins: signal (S), ground (G) and voltage (V) which are connected to the microcontroller. This one oversees reading the signal that the endstop may issue. The functionality is very simple: The common (C) is in charge of emitting the signal and it is usually in contact with the Normal Close (NC) during the whole time in which the interrupter is not pressed. When this situation changes and the interrupter is pressed, then the Common stops its contact with the NC and gets in contact with the Normally Open (NO). This change is issued by the

signal connection to the microcontroller which reads it and acts consequently with whatever is stated in the code.
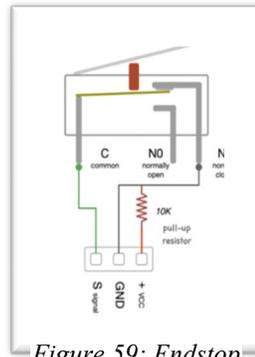
Figure 59: Endstop

In the context of this project, two mechanical endstops have been used: one for each motion direction. When the interrupter is not being pressed then nothing happened, however, when the pressing takes place is when the limit switch sends a signal that is read by the Arduino and, in consequence, it stops whichever movement that was taking place.
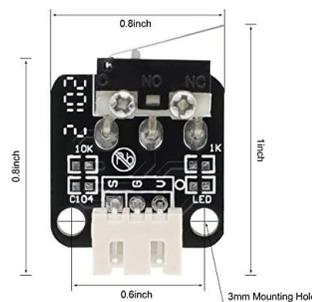
Figure 60: 3D printer endstop

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6.2   Circuit

As it has been previously described, many requirements needed electronic solutions in order to be fulfilled. Now, it is time to analyze how all the electronic components that are part of those solutions were put together into an only efficient and functional circuit. The circuit is composed of the following components:

1 Motor driver	1 Arduino UNO	3 Push buttons
1 Stepper motor	2 Limit switches	5 Resistors (1kΩ)
1 Potentiometer (10kΩ)	1 LCD display	Wires + Breadboard

Table 2: Circuit components

6.2.1   Connections

This section summarizes how all the electronic components are connected to the circuit, paying especial attention to the different pins they have:

- **Motor driver:** This is probably the most unusual component of the circuit and hence, the most complicated to connect. As seen in the figure 60, it has 16 pins (8 on each side):
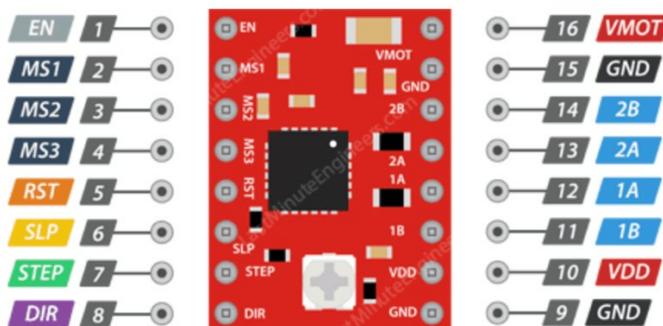
Figure 61: A499 motor driver

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On the right side of the driver, pins 9 (GND) and 10 (VDD) are used to drive the internal logic circuitry, which can range between 3 – 5 V. The power is connected to pin 10, while 9 goes to ground. On the top side, also pins 15 and 16 have power supply purposes, in this case for the motor itself. Pin 15 gets connected to ground, while pin 16 to the power, which can vary between 8 – 35 V depending on the stepper motor to which it is connected. In this case, 12 V.

Regarding pins 11, 12, 13 and 14, they are the outputs of the motor driver, and they are directly connected to the stepper motor. They can provide up to 2A to the stepper.

On the left side of the driver, pins 1, 5 and 6 are in charge of controlling the power states. They are all active low inputs, which means that they will only do their function when they are pulled low. When pin 1 (EN) is low means that the driver is enabled, hence this pin wasn't connected to anything (low mode). Pin 5 (RST) ignores all the input steps when it is set low, and pin 6 (SLP) puts the driver into "sleep mode" when low, minimizing the power consumption. Pin 5 (RST) is floating, and hence must be connected to the adjacent SLP pin (6) to bring it high and enable the driver.

Pins 2 (MS1), 3 (MS2), and 4 (MS3), on the top left of figure 60, are responsible for micro-stepping. These pins can be in a high or low state, depending on an internal pull-down resistors that give a low state if they are left disconnected. In this way, the micro-stepping is controlled as follows:

MS1	MS2	MS3	Microstep Resolution
Low	Low	Low	Full step
High	Low	Low	Half step
Low	High	Low	Quarter step
High	High	Low	Eighth step
High	High	High	Sixteenth step

Figure 62: Microstepping detail

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Finally, pins 7 and 8 are the inputs that control the stepper motor. They are both connected to the microprocessor. Pin 7 (STEP) controls the microsteps of the motor. Each high pulse sent to this pin drives the motor according to the number of microsteps determined by the microsteps selection pins. The faster the pulse, the faster the motor spins. On the other hand, pin 8 (DIR) controls the direction in which the stepper motor spins. If this pin is low then the stepper motor spins anticlockwise, if high it spins clockwise. These pins were connected to digital pins in the Arduino, number 10 and 11 respectively.

- **Stepper motor:** As stated before, the stepper motor is only connected with the four wires of the motor driver (1A, 1B, 2A, 2B). Hence, the stepper motor and the motor driver end up being connected as follows:
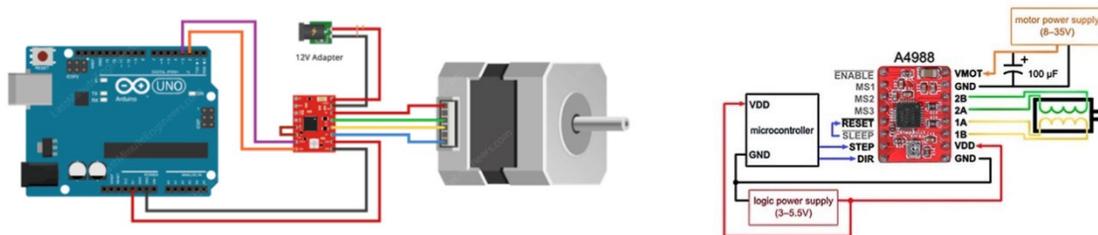
Figure 63: Stepper motor connection with motor driver

- Potentiometer: The way it works is very simple but also very interesting. The most important thing to understand its connections is to see this element as a variable resistor. It has three pins. Two of the pins are fixed, pin 1 is connected to ground and pin 3 is connected to the Arduino power (5V). The third one, pin 2 is the wiper contact, which is the output of the potentiometer that will be seen as an analogic input in the Arduino. An easy way to understand the functionality of the potentiometer is knowing that between the ground and power pins there will always be the same resistance, in this case it will always be 10kΩ. However, the utility of the element is seen when it comes to measure the resistance between one of the fixed pins and the wiper connection. The following figure explains it graphically.

FUNCTIONAL DIAGRAM   **SCHEMATIC SYMBOL**
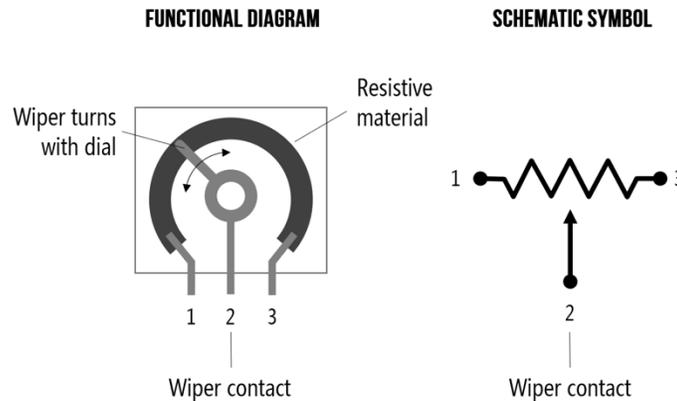
Figure 64: Potentiometer diagram

In this context, it is trivial to calculate the maximum and minimum voltage that the microcontroller senses. The signal sent by the wiper contact to the Arduino will be received as an analog input by the microcontroller. It is important to understand that this signal (and whichever sensed as an input in the Arduino) will be sent in the form of voltage, never current. The total resistance that an Arduino input is said to have approaches 100MΩ, which means that almost no current enters an Arduino input pin. Now, how does the microcontroller turn this voltage into an analogic signal? The answer is by using an Analog to Digital Converter (ADC). The resolution of this function in the Arduino is 10 bits, this means that it can convert whichever voltage between $0 – 5$ V into an analog signal of $0 – 2^{10}$ range $(0 – 1023)$. Hence, it can read changes in voltage every $5V / 1024 = 4.9mV$. For this project this level of resolution wasn't needed because, as it will later be explained in the code section, there were 9 discrete speed levels possible which reduces a lot the resolution actually needed for a correct functionality of the device.

- **LCD display:** This component has 16 pins, and hence it is not easy to connect properly. The following figure sums up the electronic logic of each pin:

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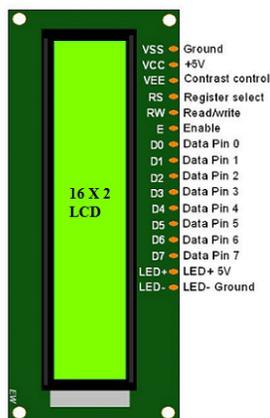
Figure 65: LCD diagram

The pins are going to be described from top (pin 1) to bottom (pin 16). Pins 1 and 2 are the power terminals of the LCD, pin 1 is connected to ground while pin 2 is connected to the power source (5V). Pin 3 (contrast control) is in charge of controlling the brightness of what is being displayed on the LCD, that is why it is connected to a certain voltage between 0 – 5 V controlled with two resistors, the highest the voltage the brightest. Pin 4 (register select) is a memory pin to select the data to be displayed. Pin 5 (read/write) selects the write (0) or read (1) mode (in this case it was write) while pin 6 (enable) must always be high to permit the read/write process. Pins 7-14 are data pins, but only pins 10, 11, 12 and 13 are used in this case because only 4 bits are needed for the process. It could have been done with 8 bits and the data would go faster, however, this effect is frankly difficult to notice and it would have occupied too many digital pins of the microcontroller. Finally, pins 15 and 16 are used as anode and cathode, respectively, of the LED that the LCD has integrated on itself.

- **Limit switch:** This component follows a very logical way to function once understood the introduction of the component made in the previous section of the chapter. It basically sends a voltage change to the microcontroller which is read as an input. The limit switch has three pins, but for this simple function only two need to be connected:

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the ground (G) and the signal (S). The normal state of the mechanical endstop will be high, because the signal is connected to the power (separated by a resistor to avoid a short circuit). When the limit switch is pushed and hence activated, the internal connection of the limit switch connects S with G and turns its mode into low. This new low state voltage is sensed by the microcontroller which reads it and acts as stated in the code.

- **Push button:** This is the simplest component of the circuit to connect. It follows the same electronic logic as the limit switch explained just before. It is always in high state until it is pressed, when it turns into low state (this is equivalent to 0 in the code). It can either be connected to a digital or analog pin in the microcontroller. It was chosen an analog pin in case the few digital pins left free were needed for any other purpose.

6.2.2 Power & Microcontroller

The power supply that the circuit needed in order to operate within its expected functions was double: 5 and 12 V. While the 12 V were only needed by the stepper motor, the 5 V were crucial in order to make all the other electronic components work: the push buttons, the potentiometer, the LCD display and the motor driver. To be able to separate those two different voltages a breadboard was used with the following configuration:
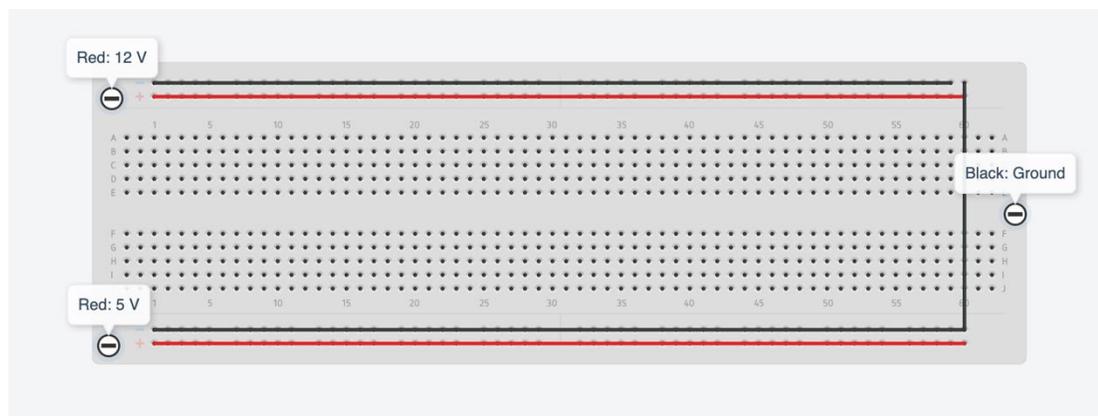
Figure 66: Breadboard scheme

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It is important to stand out that both ground references were connected so that the circuit had a unique ground reference. This was due to the problems experienced when they were not connected like this. The reason behind it is that the microcontroller reads or writes different impulses that are meant to be between 0 – 5 V. The problem is that the microcontroller expects those signals to be digital (0 or 1). If the signal was not a perfect 0 (0 V) it was sometimes read as a 1 when it wasn't. When the grounds were unified this problem stopped as there was an only reference which was the one imposed by the wall power supply.

Regarding the microcontroller, the classic Arduino UNO was used for the project as it had the perfect size, enough RAM memory and it had a friendly interface. This microcontroller oversaw setting the 5 V power supply from the source to the breadboard.

Once all the circuit has been explained and developed, the resulting diagram is showed in the following figure:
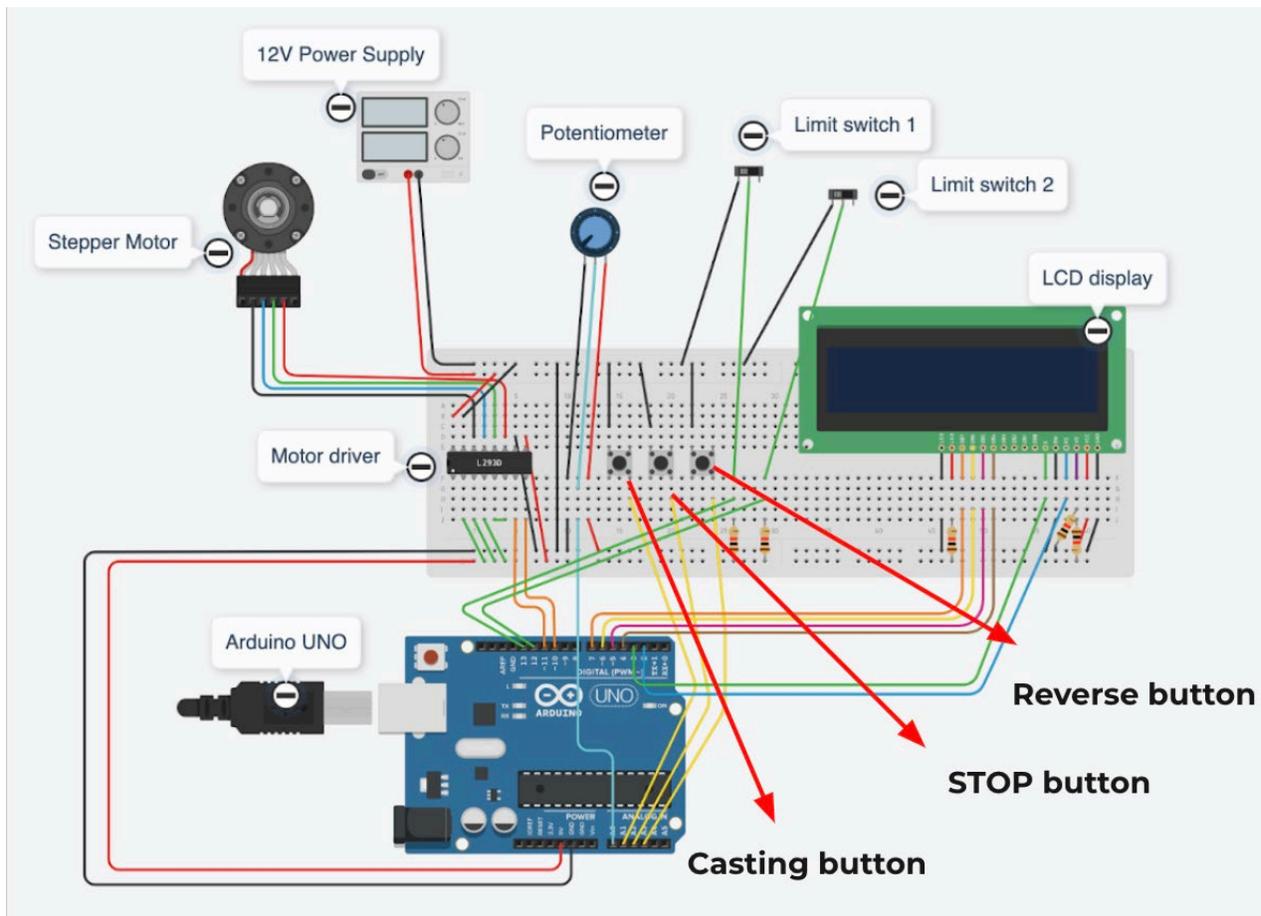
Figure 67: Final circuit

6.3   Code

Once explained the process of designing solutions to the electronics' requirements and how all the different components were put together in a circuit, it comes the time to explain how all that information was summarized and developed in a code. This step was crucial because, even if everything is perfectly designed and connected, if the code isn't right or if it is not perfectly efficient, or if it doesn't respond to all the requirements, then the apparatus won't be performing at the level expected by the clients.

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Before explaining the final code, it is important to understand the way and process in which it was written. The code is the result of weekly progresses during three months in which the electronics' requirements, the circuit and the code were designed in parallel with constant tests of the functions and actions that were weekly being implemented. It would be a total lie to say that all the electronics were designed, plugged, and coded at the same time because that would be probably impossible as it is very easy and common to make design, circuit and code errors. If it had been designed all at the same time it would have been a total chaos as it would have been extremely difficult to find, understand and solve all the problems that a big circuit like the one explained has presented during these past months.

In this context, having on mind that in his memory it would take too much space and time to describe all the code iterations, only the final code will be posted. However, to give the reader an idea of the order in which all the components were implemented and coded, this was the progress or order followed:

1) Stepper motor with motor driver
2) Stepper motor with motor driver controlled by a single button
3) Step 2 + potentiometer to regulate speed
4) Step 3 + implementation of two buttons to distinguish between the two motion directions
5) Step 4 + implementation of the stop button
6) Step 5 + implementation of the LCD display to communicate the speeds to the user
7) Step 6 + implementation of the mechanical endstop limit switches.

Now that it has been explained the progress followed during the coding it is time to analyze the content itself. To do so, before posting the final code itself, a flowchart has been prepared. The reason for that is double: 1) This diagram truly reflects in a graphical way the logical process that the code follows. 2) The flowchart helps the reader to understand the intention of the coder and therefore makes him/her able to easily identify the different steps of the code.

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The structure classifies the shape of the phrases between: <u>statements</u> (white rectangles), <u>questions</u> (blue circles) and <u>answers</u> (tilted squares, YES: green, NO: red). The flowchart is the following (zoom the page is recommended):

Figure 68: Code flowchart

Once explained the logic, order and functions that the electronics' process must fulfill, the final code is the following:

```cpp
#include <LiquidCrystal.h> //Library to make the LCD work
#include <AccelStepper.h>  //Library to make the stepper motor work

AccelStepper stepper=AccelStepper(1,10,11); //Initialization of the stepper motor: leave
pin 1 always there and free in the Arduino, Second pin: step, Third pin: direction
LiquidCrystal lcd(2, 3, 4, 5, 6, 7); //Initialization of the LCD display: connected to
those Arduino digital pins

#define potentiometer  A0  //10k Potentiometer
#define bt_W A3 // Waterbath direction button
#define bt_S A2 // Stop button
#define bt_C A1 // Casting button

int read_ADC=0; //reads the potentiometer
int duty_cycle; //reads the potentiometer
int duty_cycle_lcd; //potentiometer to LCD

int set = 0; //Var. that sets the machine state: stopped, casting or waterbath
int finalspeed=0; //Var. that sets the casting speed
int backspeed=0; //Var. that sets the speed to the waterbath direction

void setup() {
  stepper.setMaxSpeed(40000); //Max. speed that the motor can reach

  pinMode(potentiometer, INPUT); //Initialization of the potentiometer

  pinMode(bt_W, INPUT_PULLUP); //Initialization of the waterbath button
  pinMode(bt_S, INPUT_PULLUP); //Initialization of the stop button
  pinMode(bt_C, INPUT_PULLUP); //Initialization of the casting button

  pinMode(12, INPUT); //Initialization of the limit switch 1
  pinMode(13, INPUT); //Initialization of the limit switch 2

  lcd.begin(16,2);  //First message of the device when it is turned on
  lcd.setCursor(0,0);
  lcd.print(" Atomatic Film ");
  lcd.setCursor(0,1);
  lcd.print(" Casting Apparatus ");

  delay(2000); // Machine setup
  lcd.clear(); //Removes the initialization message
}

void loop() {

  while(set==0){ //In this loop until one of the direction buttons is pressed (change in
"set")

    stepper.stop(); //During this state the motor will be stopped

    read_ADC = analogRead(potentiometer); //Reads potentiometer
    duty_cycle = map(read_ADC, 0, 1023, 0, 255);  //Analyzes potentiometer resistance
    duty_cycle_lcd = map(read_ADC, 0, 1023, 1, 9); //Sets variable in one of the 9
different speed levels

    if(duty_cycle_lcd==9){  //If speed level is 9...
      finalspeed=-12000;     //Sets the casting speed if this speed level is finally chosen
```

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```cpp
  lcd.setCursor(0,0);
  lcd.print("Speed: "); //The LCD tells the user the casting speed in mm/s
  lcd.setCursor(0,1);
  lcd.print("40 mm/s");
}
if(duty_cycle_lcd==8){
  finalspeed=-10500;
  lcd.setCursor(0,0);
  lcd.print("Speed: ");
  lcd.setCursor(0,1);
  lcd.print("35 mm/s");
}
if(duty_cycle_lcd==7){
  finalspeed=-9000;
  lcd.setCursor(0,0);
  lcd.print("Speed: ");
  lcd.setCursor(0,1);
  lcd.print("30 mm/s");
}
if(duty_cycle_lcd==6){
  finalspeed=-7500;
  lcd.setCursor(0,0);
  lcd.print("Speed: ");
  lcd.setCursor(0,1);
  lcd.print("25 mm/s");
}
if(duty_cycle_lcd==5){
  finalspeed=-6000;
  lcd.setCursor(0,0);
  lcd.print("Speed: ");
  lcd.setCursor(0,1);
  lcd.print("20 mm/s");
}
if(duty_cycle_lcd==4){
  finalspeed=-4500;
  lcd.setCursor(0,0);
  lcd.print("Speed: ");
  lcd.setCursor(0,1);
  lcd.print("15 mm/s");
}
if(duty_cycle_lcd==3){
  finalspeed=-3000;
  lcd.setCursor(0,0);
  lcd.print("Speed: ");
  lcd.setCursor(0,1);
  lcd.print("10 mm/s");
}
if(duty_cycle_lcd==2){
  finalspeed=-1500;
  lcd.setCursor(0,0);
  lcd.print("Speed: ");
  lcd.setCursor(0,1);
  lcd.print("5 mm/s");
}
if(duty_cycle_lcd==1){
  finalspeed=-100;
  lcd.setCursor(0,0);
  lcd.print("Speed: ");
  lcd.setCursor(0,1);
  lcd.print("1 mm/s");
}
```

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```
  if(digitalRead (bt_W) == 0){ //If waterbatch button (black) is pressed...
  delay(50); //This delays accounts for mechanical issues when pressing the button
  set = 1; //The state of the device passes to waterbath movement
  backspeed=12000; //Chooses the waterbath speed
  }
  if(digitalRead (bt_C) == 0){ //If casting button (green) is pressed...
  delay(50); //This delays accounts for mechanical issues when pressing the button
  set = 2; //The state of the device passes to casting movement
  }
}

while(set==1){ //In this loop until stop button is pressed (change in "set") or limit
switch 2 is activated

  stepper.setSpeed(backspeed); //Sets the motor at that constant speed
  stepper.runSpeed(); //Makes the motor move

  if(digitalRead (bt_S) == 0){ //If stop (red) button pressed...
  delay(50); //This delays accounts for mechanical issues when pressing the button
  set = 0; //The state of the device passes to STOP
  }
  if(digitalRead(13)==LOW){ //If limit switch 2 is activated...
    set=0; //Stops the device, skips the loop: no more movement
    stepper.setCurrentPosition(0); //Makes the motor memorize which position is at that
moment
    stepper.setMaxSpeed(40000); //Preset of the following max. speed
    stepper.setAcceleration(100); //Preset of the following max. acceleration
    stepper.moveTo(-7400); //Makes the motor move 7400 steps in the "casting" direction--
> Makes the motor go to the initial position

    while(stepper.distanceToGo()!=0){ //Until the motor hasn't arrived to the intial
position...
      stepper.setSpeed(-backspeed); //It will move at this speed
      stepper.runSpeed(); //Constant speed
    }
  }
}
while(set==2){ //In this loop until stop button is pressed (change in "set") or limit
switch 1 is activated

  stepper.setSpeed(finalspeed); //Sets the motor at that constant speed
  stepper.runSpeed(); //Makes the motor move

  if(digitalRead (bt_S) == 0){ //If stop (red) button pressed...
  delay(50); //This delays accounts for mechanical issues when pressing the button
  set = 0; //The state of the device passes to STOP
  }
  if(digitalRead(12)==LOW){ //If limit switch 1 is activated...
    set=0; //Stops the device, skips the loop: no more movement
  }
 }
}
```

Even though not only the whole code is commented and explained (// …) but also it is assumed that the reader has at least basic programming knowledge, there are a few things that must be pointed out because they are considered as exclusive peculiarities of this project:

1) **Arduino libraries used.** In this code two different libraries have been used:

   - LiquidCrystal.h → This one won't be developed as it is very classic to see this library in a lot of engineering projects. It is the one that enables the LCD display to show information and hence communicate with the user.

   - AccelStepper.h → Even though it is not a strange library, this one is less common. It is used as an interface between the stepper motor and the microcontroller. As some of its functions have been used repetitively, it is important to describe their utility:

     o *Accelstepper Name*: initializes the stepper motor and sets the pins that are going to refer to the direction and steps of the motor. *Name* is up to the user.

     o *Name.setMaxSpeed(#)*: Sets the maximum permitted speed. # must be a positive number (steps/s).

     o *Name.stop()*: Stops the motor.

     o *Name.setSpeed(#)*: Sets the desired constant speed. # can be a positive (clockwise movement) or negative (anticlockwise movement) number (steps/s).

     o *Name.runSpeed():* Implements the speed set by the previously called function set.Speed. This function provokes the actual movement of the stepper motor.

     o *Name.setCurrentPosition(#):* Resets the current position of the motor, so that the new 0 position turns to be the current motor's position. # = number (steps)

     o *Name*.moveTo(#): Sets the target position. # (steps) can be a positive number (clockwise movement) or negative (anticlockwise).

     o *Name.distanceTogo():* It is the distance from the current position to the target position measured in steps.

2) **Initializations.** It is key to let the microcontroller know which pins are going to act as inputs and which are going to be outputs. The inputs are those pins that are initialized to read and process an external signal, in this case they were: potentiometer, three buttons and two mechanical endstops. On the other hand, the outputs are those pins initialized to issue a signal or an action to the circuit, in this case they were: the stepper motor and the LCD display.

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3) **States.** To differentiate between the different states in which the device can be working at, the variable "set" was created. This variable is crucial to set the actions of the machine. If set is equal to 0: the machine is stopped, the potentiometer and the buttons are constantly waiting to be used and the LDC displays the different speed options. If set=2, the apparatus casts the film, the LCD displays the casting speed and the only components reading are the casting limit switch and the STOP button. Finally, if set=1, the apparatus is moving back to push the substrate into the water bath, and the only two components reading are the reverse limit switch and the STOP button.

4) **Speed levels.** It is interesting to see how the variable speed requirement has been finally coded. The customers had two options: discrete steps between 0 – 40 mm/s or continuous steps. When the potentiometer was first implemented the choice was to make the steps continuous, as the easiest way to code it was that the speed had to depend on the exact % of resistance that the potentiometer was exerting. However, when both methods were tested, the most precision method turned to be discrete steps as the continuous didn't guarantee being always perfectly exact and repeatable. In this way, the customers agreed that the most convenient method was to have discrete steps to guarantee the consistency of the films. When asked about the number of different speed levels they wanted, they said that 9 were enough, one level every 5 mm/s.

Figure 69: Speed level detail

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6.4   Safety and Durability

Once all the design, circuit and code has been explained, it is time to explain some safety and durability measures that were taken in order to increase its secure and permanent use, and reliability.

Regarding the safety of its use there mainly four measures to point out:

In first place, the circuit and the code were optimized to avoid accidents during the casting process:

- Existence of a STOP button that could stop the casting process in whichever moment.
- The potentiometer was set to be read only when the apparatus hasn't started casting in order to avoid sudden changes in the casting speed in case of an accidental spin of it. Hence, once the casting button has been pressed the potentiometer stops being read and the casting speed cannot be accidentally changed.
- The reverse speed that pushes the glass slide back to water bath has been set to be constant and fixed, hence it does not depend on whichever casting speed has been chosen by the user. In this way, the reverse speed is ensured to not be too fast to make push the glass slide too fast to make it fall outside of the nonsolvent bath.

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CHAPTER 6 – ELECTRONICS' DESIGN

Secondly, to ensure the safety of the electronics design an electronic box was required which was meant to keep inside of it all the electronic components connected in the circuit. First of all, a common box was bought such as the one in the following figure:

Figure 70: First electronic box

However, when presented to the customers this box was rejected because it made the overall design of the apparatus very uncomfortable to be working with as it meant to have the electronics and mechanical designs very separated the one from the other and it could create a problem to have both boxes connected externally with cables. Hence, they suggested a more compact design in which the wires were connected internally instead. It must be remembered that the wires that had to go from the electronics box to the mechanical housing were the two mechanical endstops, the stepper motor and the power supply.

In this context, a new electronics box was designed and 3D printed which allowed to be joined to the mechanical design at the same time it allowed the wires to pass through. The sketch of the final electronics box can be found in the Appendix E. The most important feature of the design is that it was perfectly thought to be friendly with the user in terms of comfortability. This can be appreciated in the angle in which the control center of the electronics was designed, which

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perfectly allows to the user reading the LCD display without having to step back from the apparatus.
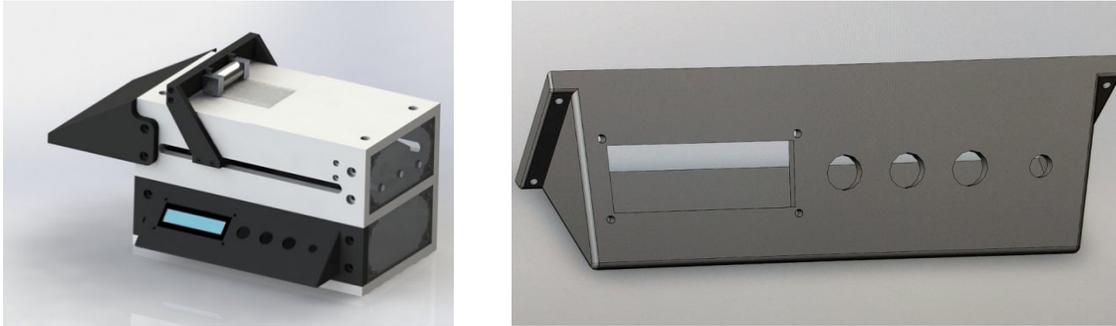
Figure 71: Final electronic box design

In third place, as it can be seen in the figure above, covers were inserted in the sides of the mechanical housing and in the electronics box. The reason for this was double:

1) Protecting the inside circuit and mechanical design from dangerous external agents (especially the corrosive DMSO and the water from the precipitation bath that could splash and wet the circuit).

2) Protecting the user from any internal circuit shortcut or mechanical issue that could create danger.

The most relevant topic to point out from the design of the side cover pieces is the material of it. They were made from PP (polypropylene) due to its transparency to see the components as well as its chemical resistance.

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CHAPTER 6 – ELECTRONICS' DESIGN
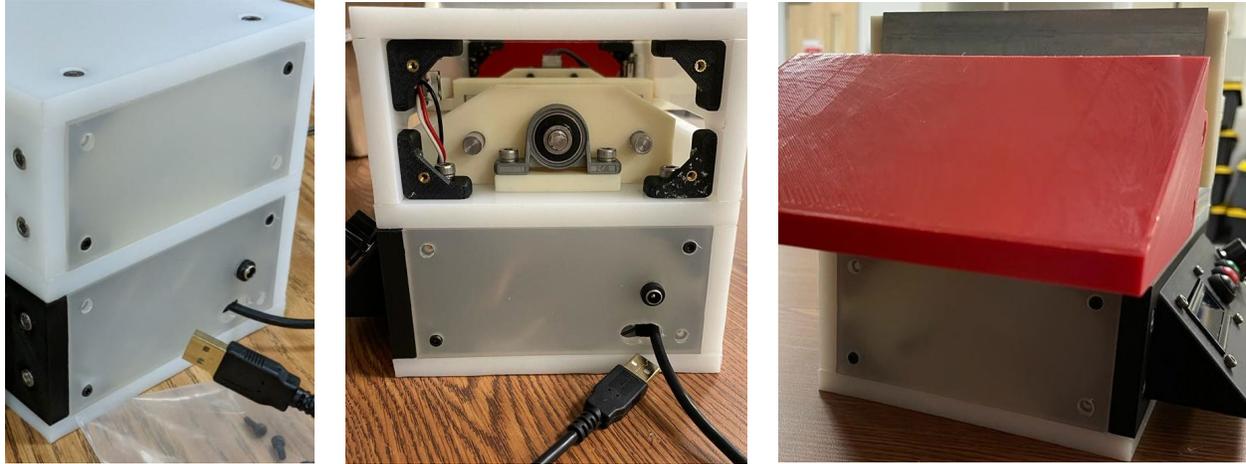
Figure 72: Wire protectors

Finally, the fourth and last thing to point out from this section is a measure to ensure the durability of the device. It consists of soldering the whole circuit and fixing it to the electronics box. Although the results of this will be showed through pictures in the next chapter, the following figures show the holes made in the structure of the housing to screw the electronics:
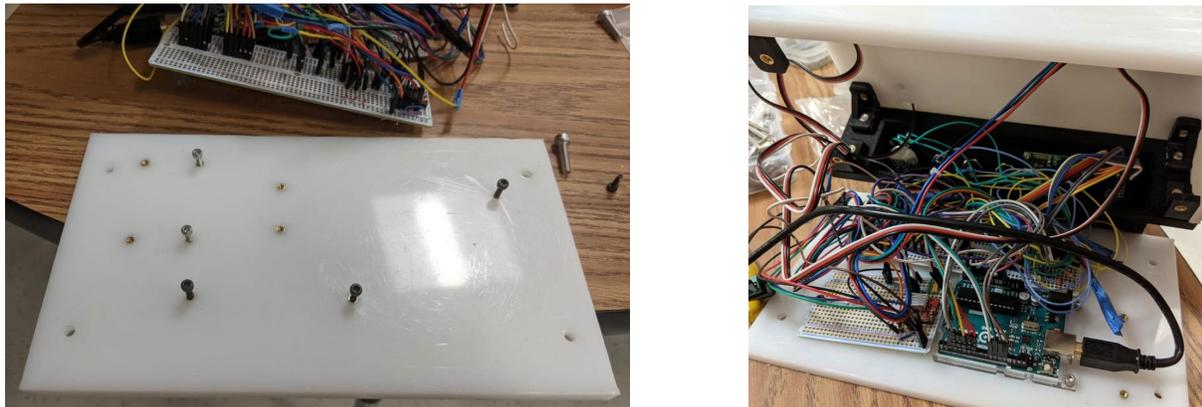
Figure 73: Electronics screwed detail

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CHAPTER 7 – ANALYSIS OF THE RESULTS

CHAPTER 7. ANALYSIS OF THE RESULTS

7.1 Mechanical design results

In order to show the results and progress of the mechanical designs plenty of pictures were taken from the SolidWorks CAD design and the final apparatus already machined and mounted:
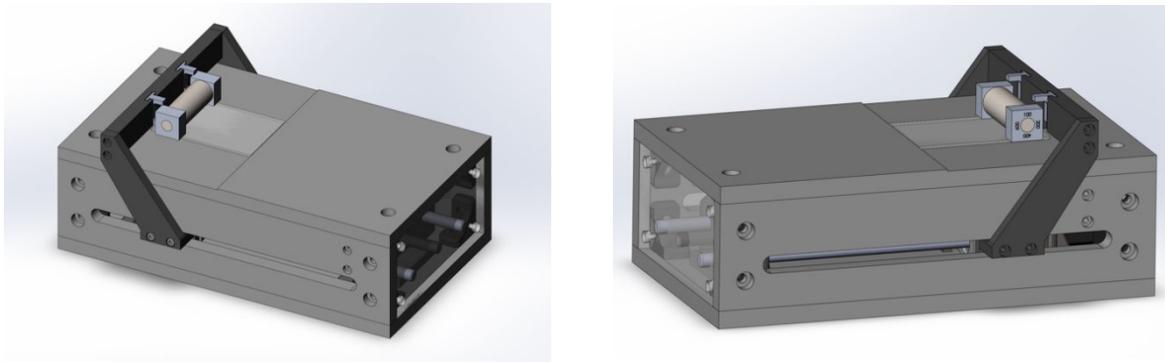
Figure 74: Mechanical CAD design
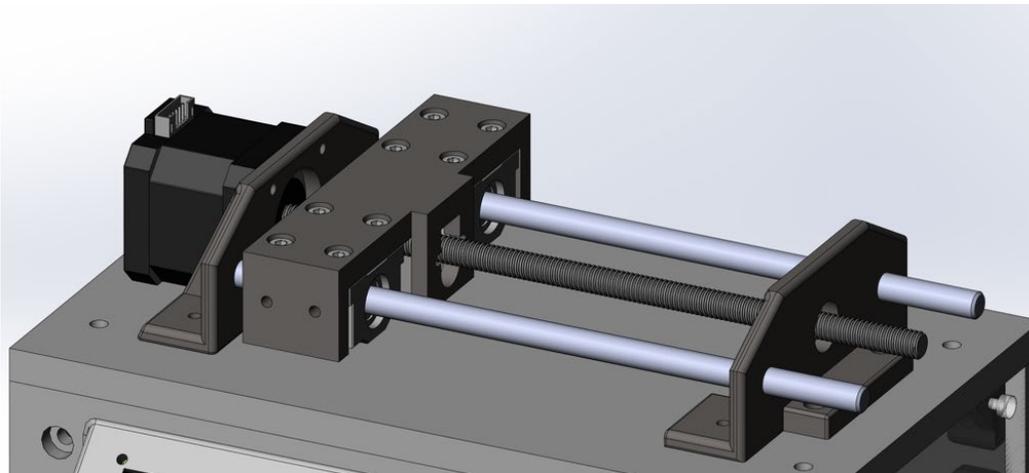
Figure 75: Detail on the CAD design of the movement

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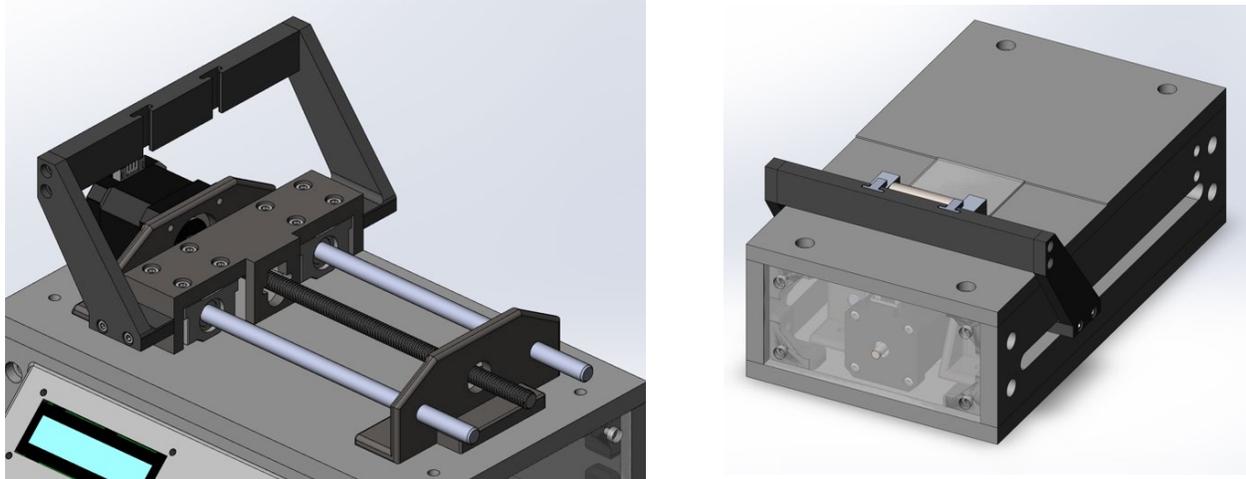
Figure 76: Push bar CAD detail
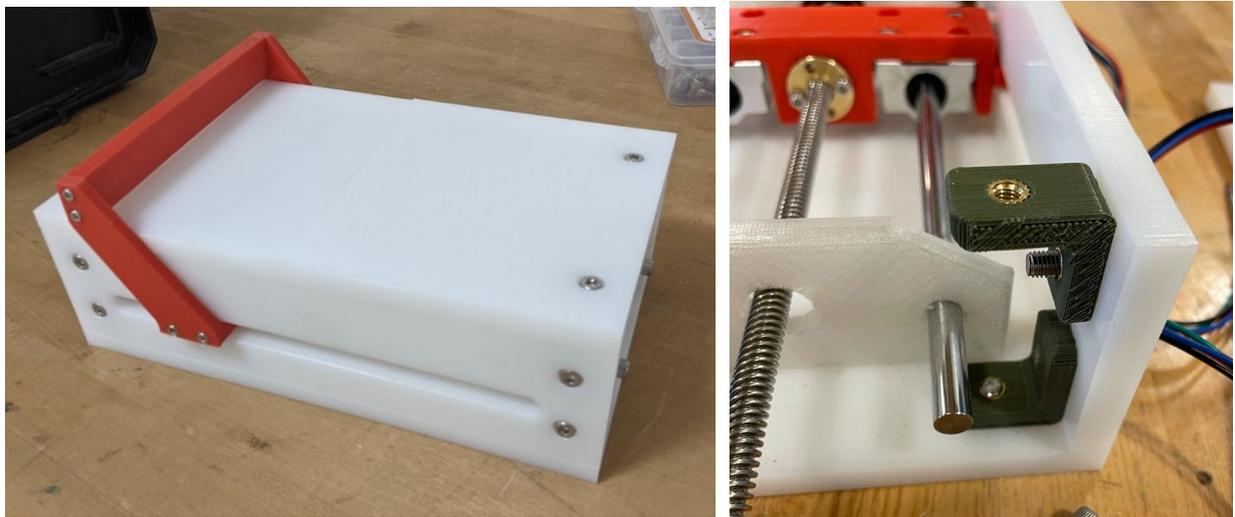
Figure 77: Final housing detail

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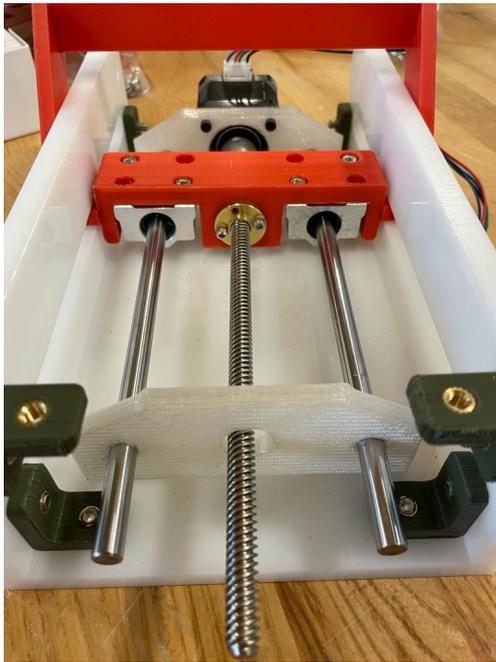
Figure 79: Lead screw

Figure 78: Doctor blade on glass slide

Figure 80: Side view of the mechanical design

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7.2   *Electronics design results*

In order to show the results and progress of the electronics designs plenty of pictures were taken from the basic and soldered circuit, and the electronics implementation:
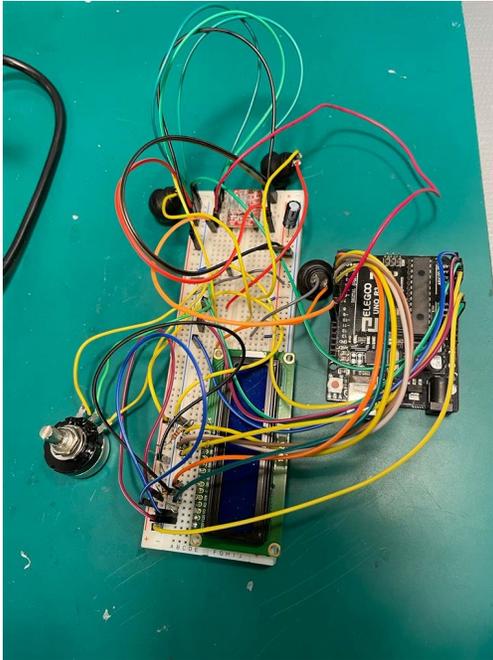
Figure 82: Basic circuit
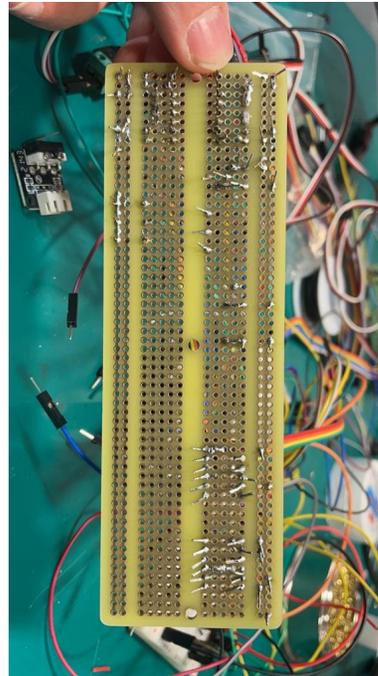
Figure 81: Soldered circuit
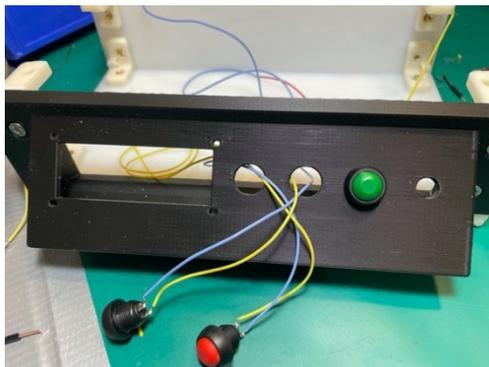
Figure 84: Electronics assembly
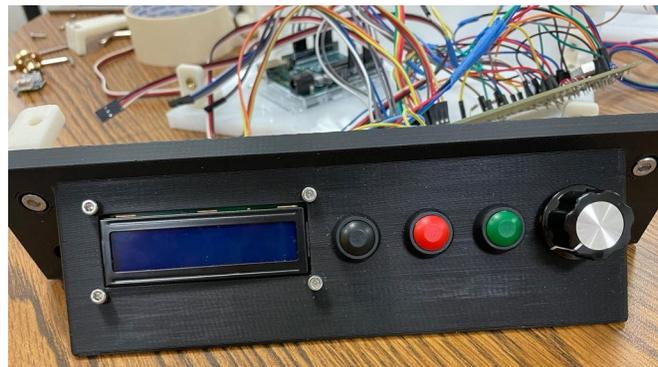
Figure 83: Detail of the electronic box

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Figure 86: Front view of the endstop
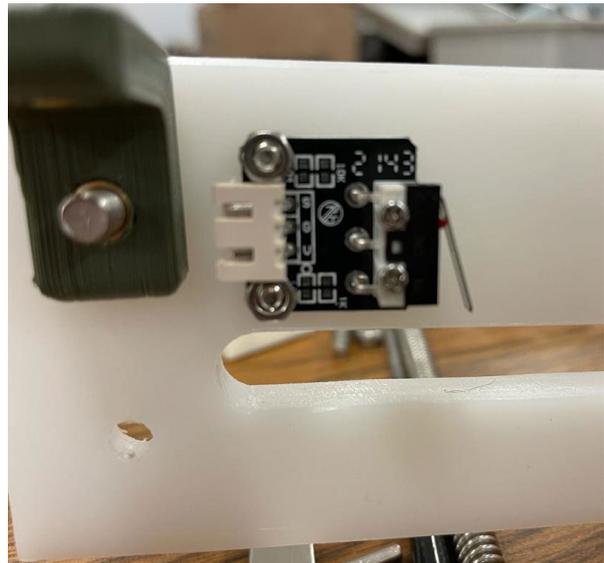
Figure 85: Side view of the endstop
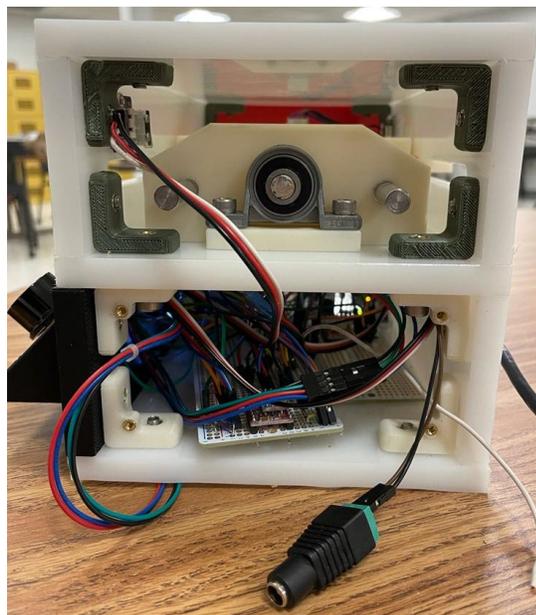
Figure 87: Side view of the final electronics assembly

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7.3   Final device: mechanical and electronic designs assembled
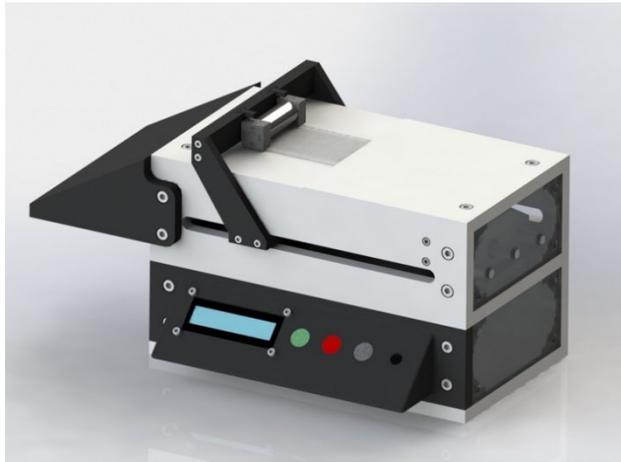
Figure 89: Final CAD design

Figure 88: Final manufactured result

Figure 91: Side view of final product

Figure 90: Final producto ON

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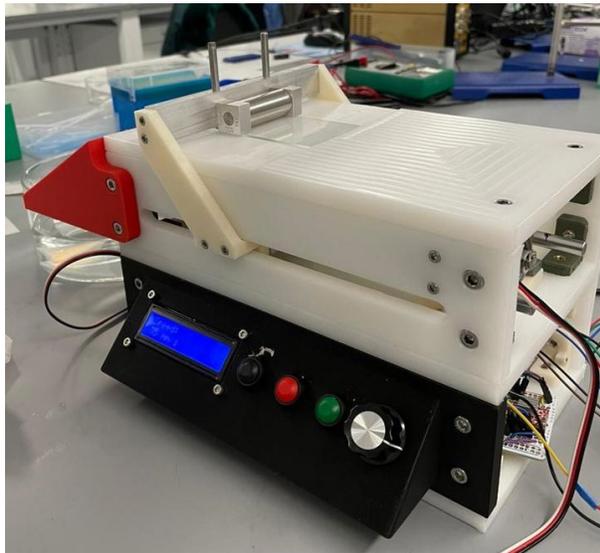
Figure 93: Final producto before covering

Figure 92: Final producto covered
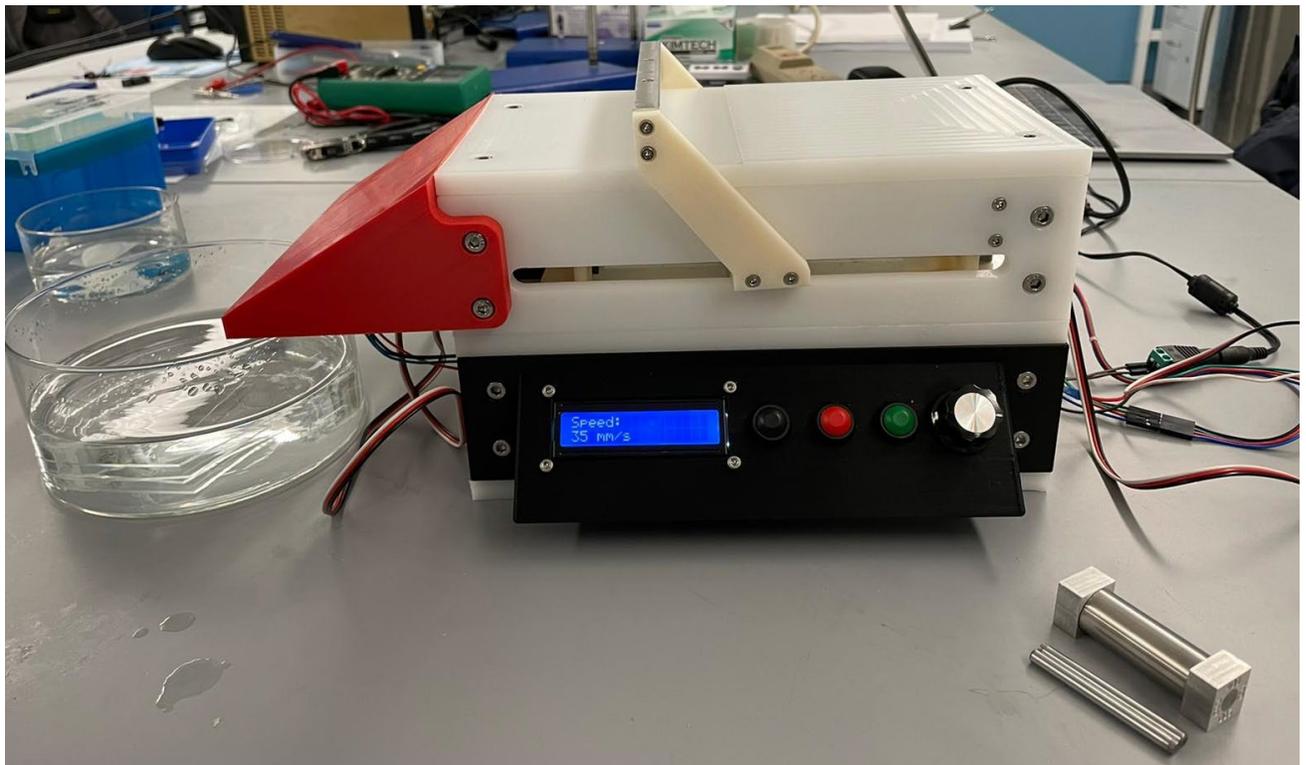
Figure 94: Detail on the final device

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7.4 *Manual doctor blade test*

After the fabrication of the doctor blade, it was tested in the customers' lab (Werner lab) to mainly check four standards:

1) If the surface of the bought cylinder was polished enough to cast at a high consistency level and its cleanability.

2) To check if the aluminum blocks of the sides (that were in charge of setting the casting thickness) had been perfectly joined and there were no sloped cross-sections (same thickness in the whole casting surface).

3) To check if the four casting thicknesses were as precise as demanded by the customers.

4) To check the overall functionality of the optimized process: moving doctor blade and stationary glass slide.

It is important to state that when the doctor blade was first tested, the electronics design hadn't been yet completed and hence it was not possible to test the whole assembly together. In this way, what was tested was the doctor blade itself in a manual way. These tests were important, not only because the design had to be revised, but also because they were going to be manual, same casting method as the one that had been done until then and, therefore, the customers were going to be able to directly compare the results between the new project's doctor blade and the one that they had been using until then: the *BYK Instruments* doctor blade (explained in chapter 4).

The main reason to worry before the tests was to see if the doctor blade met the consistent cross-section at the 100-micron level which required tight tolerances to the machine. Since the error in the doctor blade manufacturing would be most present in the smallest layer height, it was tested at that metric first. The DMSO films were cast and images were taken at multiple locations using pixel counting to measure the film thickness.

Before showing the results, it is important to remind the reader that once the films are cast and placed in a water bath to solidify, they shrink. As a result of this, as previously stated, the aim of

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the different cast thickness is not to get a solidified membrane of 100 microns, but a uniformly thick membrane below 100 microns. An SEM (Scanning Electron Microscope) picture of the 100-microns cast film is shown below.
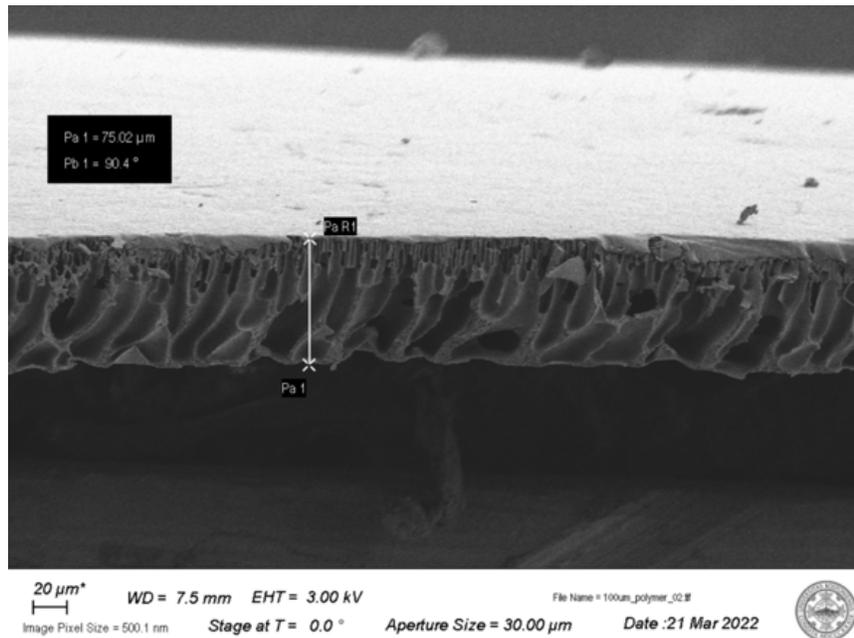
Figure 95: Cast membrane during manual method test

The scale of the picture can be appreciated in the down-left corner of the picture (20 micron). The result of the shrinking process during the solidification of the membrane can be seen in the measurement of the cross-section with which the customers provided the picture. As it can be seen, the 100-micron level battery electrode shrinks to 75 microns.

In addition to this figure, the customers also provided one in which the consistency of the membranes can be appreciated in more detail as the SEM picture has been taken from a scale of 100 microns (down-left corner).

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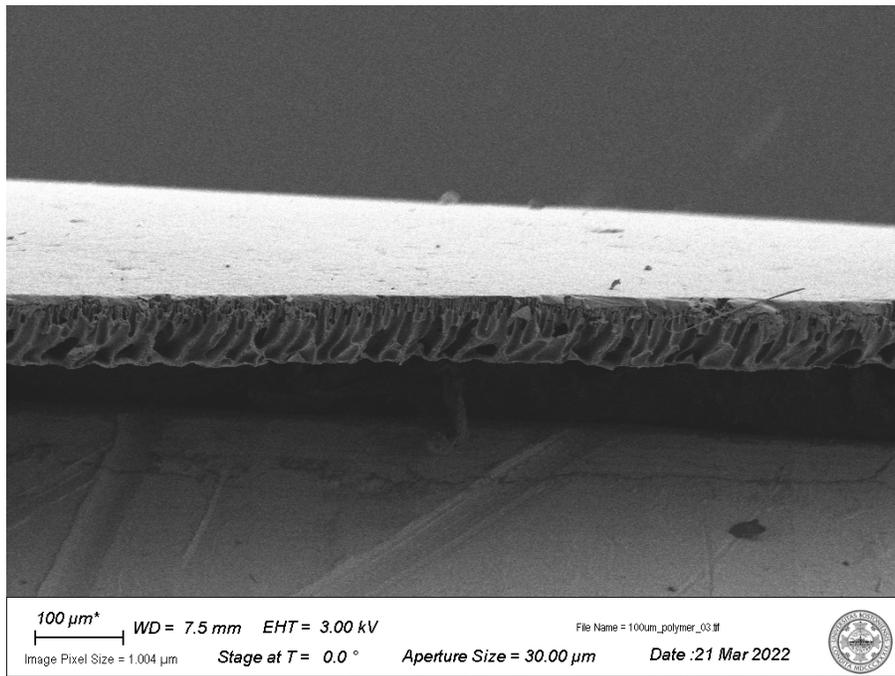
Figure 96: Detail of the cast membrane

After evaluating the results of the most worrying thickness, the customers were satisfied with them and visually confirmed that the films cast at 100 microns were of uniform cross-section when compared to the previous doctor blade used. What had to be appreciated in figure 94 in order to check if the result was successful is:

1) If there was a flat and consistent surface of the cast battery electrode.
2) If the thickness of the cross-section was homogeneous.

Both checks were successful. Since the customers were satisfied, no further quantification of metrics was explored as it was not necessary. Nevertheless, it must be stated that there was still margin for improvement as they noticed the formation of small bubbles in the top part of the film (the closest to the surface). They did not give too much importance to those bubbles as they were seen as something normal taking into account that the casting speed had not been perfectly constant due to the manual method.

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Once the 100-micron layer passed testing, it was predicted that the other layers would pass as well, but they were tested as a double-check. They can be seen in the following figures:
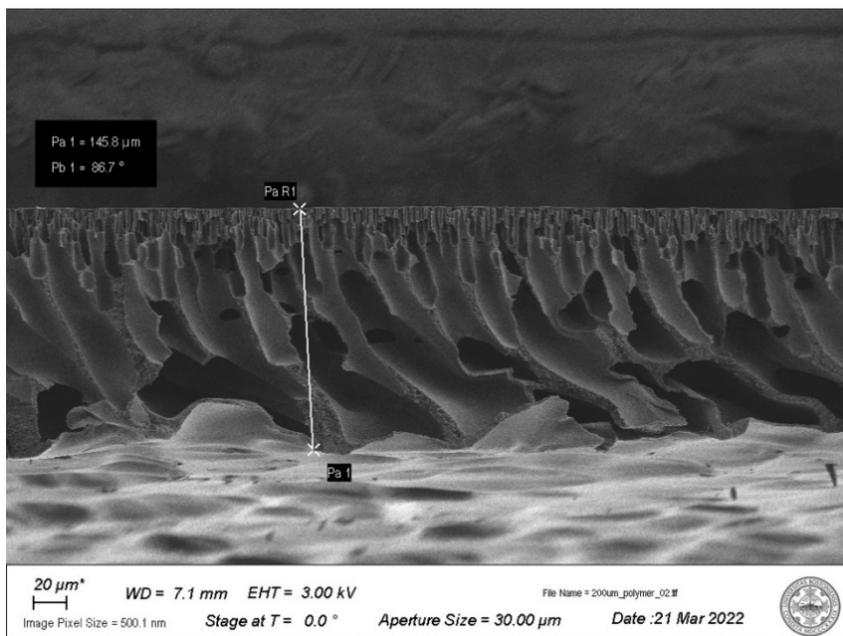
Figure 98: Cast membrane at 200 micron
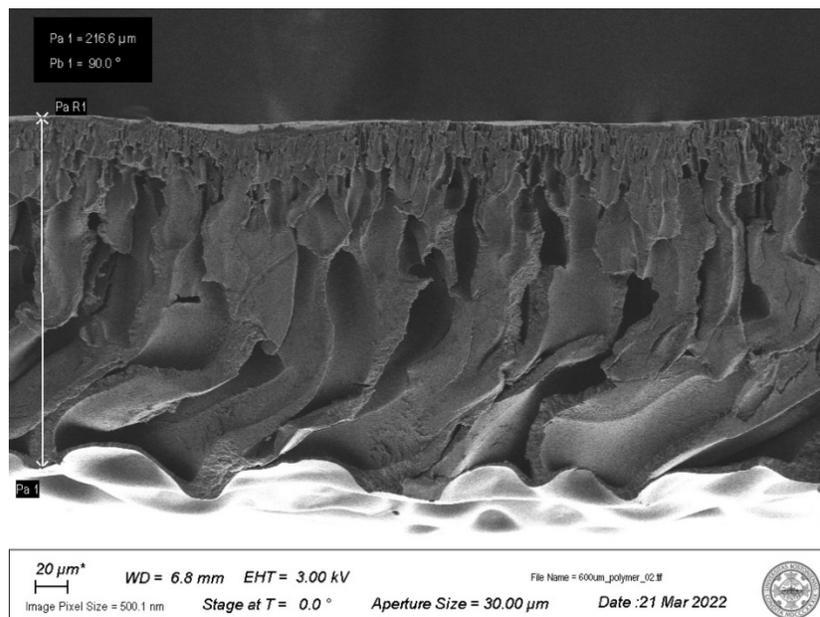
Figure 97: Cast membrane at 400 micron

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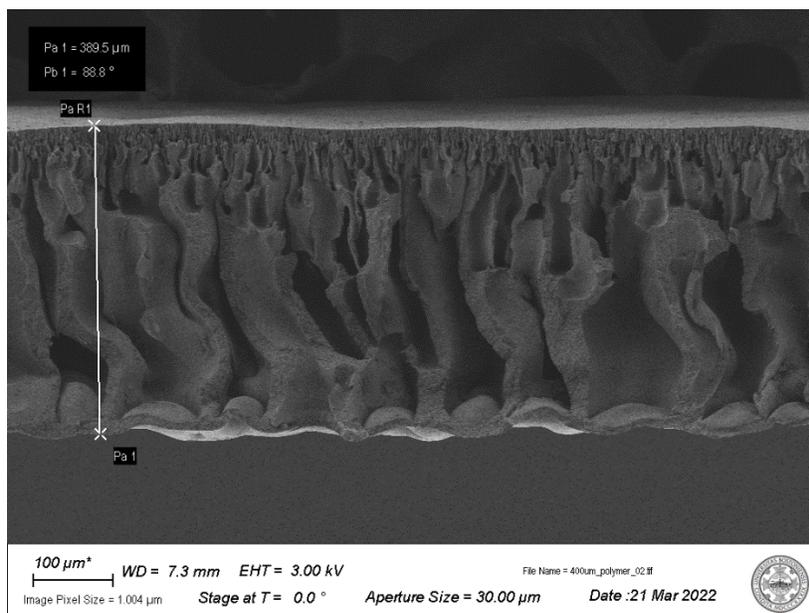
Figure 99: Cast membrane at 600 micron

The films at all other thicknesses were of uniform cross-section and the Werner's lab was satisfied with the results (except for the little bubbles already explained). Moreover, it is also interesting to see that figures 94, 95 and 96 have been taken at the same scale (20 μm) and it can easily be observed the increment in the thickness of the resulting battery electrodes.

Finally, the following table is provided to visually see the shrinking effect in the solidification of the battery electrodes. The customers admitted that the deviation percentage does not have any relevance on their later study if consistency was found between all the battery electrodes cast at the same thickness. Hence, this means that as long as all the films cast at, for example, 200 microns have a deviation of 27.10% the results would be successful as it would mean that the consistency has been achieved at that micron level.

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Casting Thickness (µm)	Post-solidification Thickness (µm)	Deviation %
100	75.02	24.94%
200	145.80	27.10%
400	216.60	45.85%
600	389.50	35.08%

Table 3. Detail of the shrinking process

Despite not having relevance for the later research of the customers, it is interesting to see that the thicker is the film cast, the bigger is the shrinking effect.

7.5   Doctor blade test with assembly

After joining the electronics and mechanical designs in an only apparatus, the assembly showed in section XX (poner la de electronics design results) was ready to be tested. As it has previously been described, the doctor blade had already resulted to be successful. Therefore, the tests that had to be executed regarded testing if the completed assembly was able to give more consistency to the cast battery electrodes than when they were cast manually. In that context, two tests had to be done. The first one was aimed to test the actual capability of the stepper motor to give a constant speed and to make that speed variable in the slots that the customers wanted. The second one was aimed to test if the thickness consistency of the membranes improved as it was expected in the automated device.

7.5.1   Casting speed test

In order to provide the customers with constant but also precise speeds the doctor blade was tested with the final assembly. First, it was concluded that the maximum number of steps the stepper motor could give with no saturation was 12,000 steps/min. That was going to be the stepper motor setting with the maximum speed that the device was going to be able to provide to the customer's casting process. After doing the tests it was concluded that 12,000 s/m translated to more or less 40 mm/s, this was the speed desired by the customers. Hence, after approving this maximum speed, they specified to divide the number of steps linearly between the nine-speed

levels from 0 to 40 mm/s. For every speed level, the configuration of the stepper motor was decreased 1,500 s/m. Using a constant distance of 75 mm (glass slide length), while timing the traversed distance, they yielded the following speed results (speed=distance/time):

SPEED LEVEL:	Test 1 (s)	Test 2 (s)	Test 3 (s)	Average time (s)	Distance (mm)	Average Speed (mm/s)	Speed (mm/s)	Motor steps
1	40,22	39,97	40,95	40,38	75	1,86	1	100
2	13,56	13,23	13,27	13,35	75	5,6	5	1500
3	7,46	7,68	7,34	7,49	75	10,0	10	3000
4	5,29	5,41	5,34	5,35	75	14,0	15	4500
5	3,88	3,79	3,88	3,85	75	19,5	20	6000
6	3,10	2,98	3,07	3,05	75	24,6	25	7500
7	2,45	2,43	2,42	2,43	75	30,8	30	9000
8	2,11	2,22	2,14	2,16	75	34,8	35	10500
9	1,85	1,83	1,89	1,86	75	40,4	40	12000

Table 4: Casting speeds results

7.5.2   SEM test of doctor blade with assembly

Since the doctor blade had passed testing manually, all that was left was to place it on the assembly to test if the constant casting speeds would yield favorable results. When the final apparatus was assembled and the speed tests had already been done, the whole final device was then tested in the Werner lab, as it had been done months before in a manual way, but this time with the automated method included.

At all thicknesses, the cast films were of uniform thickness within and across samples as well. A SEM photo of the cast film at 100-microns is shown below:

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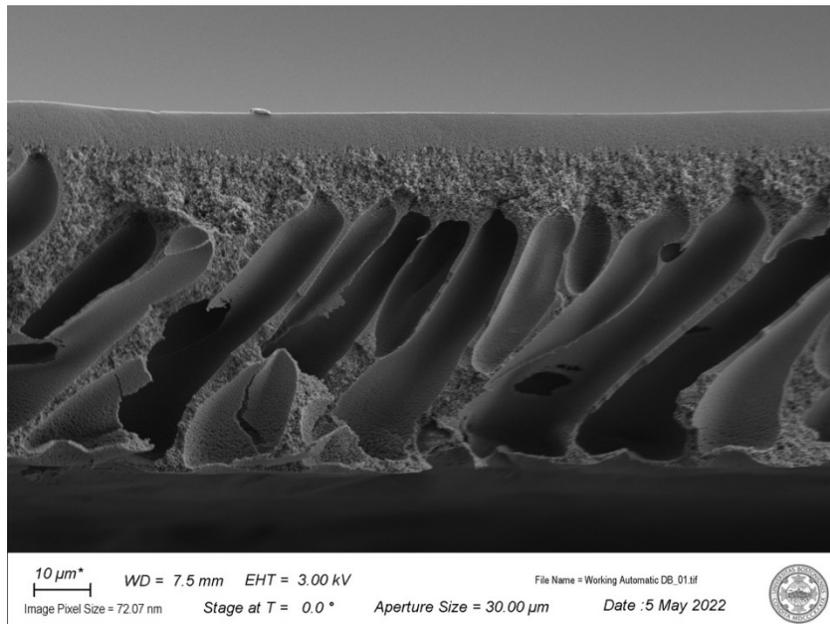
Figure 100: Cast membrane during automated method test

There are two conclusions that are especially relevant to make. Both have to do with the comparison of this result with the obtained in the manual test of the doctor blade:

1) **Overall consistency of the battery electrode.** If figures 93 and 94 (above) are compared, it can be clearly noticed that the battery electrode cast once the device had been automated is more consistent. Figure's 98 surface is much flatter, and it doesn't have the small cracks that had been formed when the membrane of the manual method test was solidified.
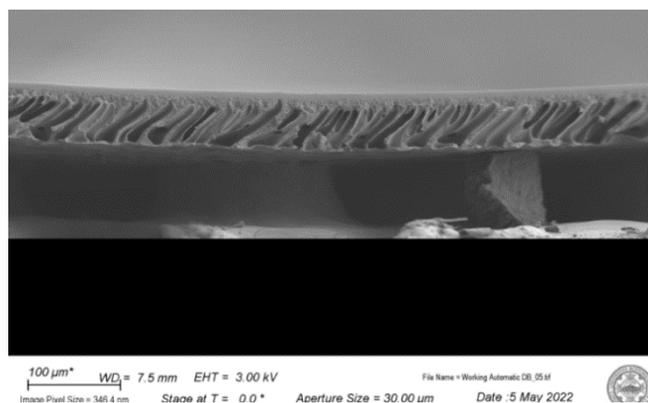
Figure 101: Detail of the cast membrane

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2) Bubbles. Below, a very detailed picture of the top surface of the membrane can be observed. The scale used in this case is 1 μm to provide the highest level of detail possible. Comparing this figure to figure 93 it is clear that in this case the bubbles that provoked not casting at casting speed have been reduced exponentially.
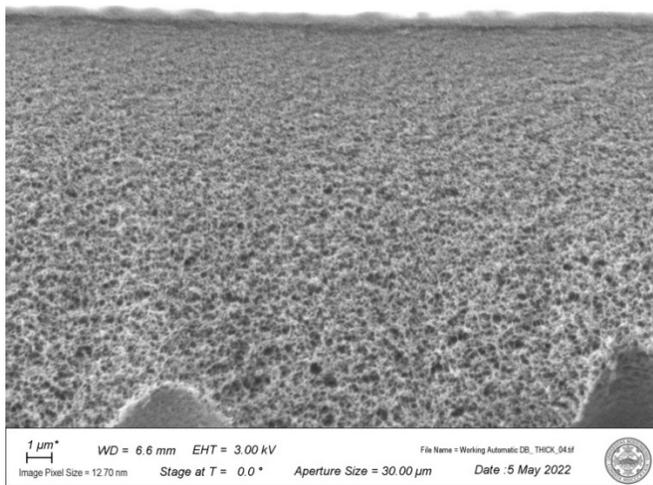
Figure 102: Detail of the bubbles

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CHAPTER 8 – SDG'S + MARKET/COST ANALYISIS

CHAPTER 8. SDG's & COST ANALYSIS

8.1 Alignment with Sustainable Development Goals (SDGs)

Figure 103: SDGs logo

The Sustainable Development Goals (SDGs) are a collection of 17 interlinked global goals that are thought to be a "blueprint to achieve a better and more sustainable future for all". These were instituted by the United Nations General Assembly in 2015 and they are meant to be achieved in 2030. The automated film casting device aligns with the following SDGs:

Figure 104: Detail of the SDGs involved in this Project

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CHAPTER 8 – SDG'S + MARKET/COST ANALYISIS

-   **Goal #7: Affordable and Clean Energy.** *Ensure access to affordable, reliable, sustainable and modern energy for all.* Nowadays, battery storage is a crucial part of the transition to clean energy because of the way it can store power from intermittent sources for use at other times, providing a cleaner and less expensive alternative to natural gas power plants. Much of the focus of the batteries' research is only being put on new material combinations so that batteries can maintain their initial properties for a long time (Li-O2 is gaining a lot of importance). The research objective why this device is needed plans to do exactly the same but focusing the research on how the durability and efficiency of the actual batteries can change putting the eye into the architectural base of the membranes that form them.

-   **Goal #9: Industry, Innovation and Infrastructure.** *Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.* This project aligns with the innovation objective for two reasons: (1) innovation of the research objective and (2) innovation of the device itself. The research objective aligns with the 5th target of the #9 goal because it enhances the scientific research. In addition, the apparatus adjusts with this goal because it pretends to be an affordable design of what nowadays is very expensive in the market (see section 2 state of the art), facilitating the access to these kinds of research activities in developing countries.

-   **Goal #12: Responsible consumption and production.** *Ensure sustainable consumption and production patterns.* The research on battery electrodes plans to increase the batteries durability and their efficiency. Hence, if the batteries are more durable, the number of batteries produced will be reduced. This will also contribute to the responsible consumption of electronic devices, reducing the electronic waste which, according to a UN report, in 2019 had an average of 7.3 kg per person.

-   **Goal #13: Climate action.** *Take urgent action to combat climate change and its impacts.* One of the main goals to fight climate change is the transition from using fossil fuel

resources to renewable energies. This impacts directly to the transport industry, especially cars. To reduce the CO2 emission, the industry of cars is already taking a step forward with the use of electric cars. These work with batteries that store electric energy. However, many people still refuse to buy them because they doubt on the efficiency and durability of these batteries. If the research that Werner's lab plans to do succeeds, the industry of batteries could be affected, be more reliable and take action against climate change.

8.2   Cost Analysis

Although the apparatus designed can seem too specific, in fact it is not. It is perfectly usable or easily adaptable to be part in a wide variety of purposes, following different processes and with different materials. Film casting is not only a process used in the Werner lab to cast phase inversion membranes for battery research. It can be seen in many different industries. Outside of the lab, doctor blades are used, for example, in cast films like tape in mass quantities. However, since the film casting apparatus is a benchtop applicator, it casts films in small batches, which limits its market to more of a research-focused group, which is who it was originally designed for.

A large part of the film casting market is taken up by labs researching battery electrodes. But there many kinds of different research in which the device would be useful at. To manufacture a lithium-ion battery, for instance, electrodes are coated in a thin film using a doctor blade at submillimeter levels. In that context, the apparatus would be able to also benefit labs conducting other research in batteries. Moreover, in the lab, film casting is not only used for DMSO (solution used in Werner lab), but for various other polymers as well. Thus, labs doing research with whichever thin film would also be able to benefit from the device.

Once introduced the great amplitude of film casting markets in which the apparatus would be useful at, it is crucial to analyze how efficient the device is in terms of costs compared to the already existing solutions of the market. Some of the most relevant market options have already been developed in the state of art section of this report and it must be said that there are a couple

of factors that set the film casting apparatus apart from commercial ones. The main difference has already been developed in the results chapter: it is related to the solidification process (automated vs manual). Since film casting devices on the market are not only used for phase inversion membranes, but for other polymers as well, some polymers do not need to be placed in a water bath, thus it is usually not seen commercially. However, since the customers exclusively cast DMSO, automated solidification was a plus.

Nonetheless, the other main difference is the cost associated with commercial options. The designed film casting apparatus is far cheaper than the market opportunities, and also it is adaptable to almost every condition that a potential new customer would require. The research and development cost of the film casting apparatus was just under $400, which was one of the most important constraints of the project. It is obvious that, once analyzed the successful results, it saves a lot of money when compared to commercial options. For example, the *byko-drive S* described in the state of art chapter retails at $4078, which is more than 10x the total cost of this project.

8.3 Expense tracking

One of the best advantages of actually having done all the research and building of the apparatus is that for the cost analysis there is no need to rely neither on budgets, nor on expectations. Only facts and real expenses must be revised in order to build an economic survey that reflects the overall cost of the device. The initial budget financed by Boston University was $400, and it was one of the most important constraints to follow. As it was money given by an institution, there has been a strict expense tracking during the whole project to ascertain that this money was only used in research purposes and with the success of the project as the only intention. Hence, it has been possible to elaborate the following table which sums up all the items bought, the quantity, the supplier (to press the links go to the appendix), the price and the date (MM/DD/YYYY) when the order was placed:

Date	Item Name	Quantity	Link	Total Price
11/13/21	Stepper motor controller w microstepping	5	https://www.amazon.com/BIQU-Compatible-	$10.99
11/22/21	Corrosion-Resistant 316/316L Stainless Steel Rod (3/4in diameter and 1/2 foot length)	1	https://www.mcmaster.com/89325K17/	$12.20
11/23/21	Multipurpose 6061 Aluminum (7/16in Thick, 6in x 6in)	1	https://www.mcmaster.com/9246K483/	$16.92
1/26/22	3D Printer Part End Stop Limit Switch	5	https://www.amazon.com/gp/product/B09K7	$8.99
1/2/22	LCD Display	2	https://www.amazon.com/dp/B00HJ6AFW6?	$9.19
2/14/22	Socket Head Cap Screw Assortment	1	https://www.amazon.com/dp/B0777HNR67?	$22.99
2/15/22	M3 Heat Set Inserts w/ Soldering Iron Tip	30	https://www.amazon.com/Insert-Inserts-Com	$15.95
2/22/22	M5 Heat Set Inserts	50	https://www.amazon.com/dp/B08T9W17CR?	$12.99
3/15/22	Moisture resistant HDPE sheet (12"*24"*1/2")	1	https://www.mcmaster.com/8619K472/	$27.81
3/28/22	TMC2209 V2.0 Stepper Motor Driver	5	https://www.amazon.com/gp/product/B09BK	$19.99
3/29/22	2pcs RV24YN20S 10K Potentiometer	2	https://www.amazon.com/gp/product/B0795	$11.99
4/13/22	Plastic Project Boxes for Electronics	1	https://www.amazon.com/dp/B09BJCP428/re	$33.99
4/14/22	M5-0.8 x 12mm Socket Head Cap Screws	1	https://www.amazon.com/gp/product/B07L8	$8.49
4/23/22	Moisture resistant HDPE sheet (12"*24"*1/2")	1	https://www.mcmaster.com/8619K472/	$27.81
4/24/22	Polypropylene Sheet 12" x 24" x 1/4", Semi-Clear White	1	https://www.mcmaster.com/8742K235/	$29.52
4/30/22	M3 Socket Head Cap Screw Assortment	1	https://www.amazon.com/gp/product/B07CX	$11.99
5/1/22	M5 Socket Head Cap Screw Assortment	1	https://www.amazon.com/gp/product/B07SB	$8.99
5/2/22	M3 Heat Set Inserts	100	https://www.amazon.com/gp/product/B08T7	$14.39
5/3/22	M5 Heat Set Inserts	50	https://www.amazon.com/gp/product/B08T9	$12.99
6/5/22	Moisture resistant HDPE sheet (12"*24"*1/2")	1	https://www.mcmaster.com/8619K472/	$27.81
6/5/22	Multipurpose 6061 Aluminum (7/16in Thick, 6in x 6in)	1	https://www.mcmaster.com/9246k483/	$16.92
6/5/22	Stainless Steel Feeler Gauge	1	https://www.amazon.com/dp/B07XPD9L1C?p	$14.99
6/5/22	5.5 x 2.1 mm DC Power Jack Socket	6	https://www.amazon.com/dp/B08SJM2G52?	$10.90
6/5/22	Double head Engraving Marking pen	2	https://www.amazon.com/dp/B07SBGQ7WW	$7.99

Table 5: Expenses detail

The rows that are shaded in red correspond to the components which although being bought, they were never finally used. It was important to register those purchases to have the correct overview of the remaining budget. Nonetheless, those components must be taken out when accounting for the total cost of the device.

In this way, to manufacture an additional copy of the final product would cost about $400. Since some of the electronics were sourced from old scrapped projects such as the stepper motor and the Arduino, there was margin to sabe some money on the electronics. Given that a stepper motor costs $15 and an Arduino costs $25, adding in extra costs like wire, breadboards, and misc electronic components would add up to $100 for the electronics as an overestimate. If the expense tracking spreadsheet omits the items not used in the final device, the cost ends up being $283.09. Adding on the $100 explained before would total just about $400.

Total Budget	**$400,00**
Total Amount Spent	**$396,79**
Total Remaining Budget	**$3,21**

Table 6: Budget detail

Finally, to manufacture a fully-fledged out model of the product with premium components would cost about $550. To improve the cleanability and chemical resistance of the apparatus Teflon can be used for the surface of the casting apparatus because of its extreme resistance to chemicals. However, a sheet of Teflon suitable for the top of the casting assembly would cost about $100-150 in raw material. This upgrade would bump up the reproduction cost to about $550 for an optimized film casting apparatus.

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CHAPTER 9 – CONCLUSIONS

CHAPTER 9. CONCLUSIONS

The most important conclusion to extract and the one that sums up the results it that, ultimately, the project function, casting sub-millimeter battery electrodes was achieved. The device was able to swiftly glide the doctor blade across a glass slide with a viscous solution on top of it. Once the solution was cast, the glass slide was pushed off of the apparatus and into a water bath. The customer then retrieved the glass slide from the water bath and evaluated a cross-section of the electrode using a scanning electron microscope (SEM). It was then reported that the results passed their tests and were consistent throughout.

The most important objective of the project must be remembered: providing the customers with an automated device that could help them to reach the consistency they needed in the battery electrodes in order to do their later research. This objective was achieved as the battery electrodes cast in the final tests turned up being homogeneous not only in their cross-section, but also between the different membranes that were cast.

9.1 Conclusions regarding objectives

When checking other objectives that the customer set up at the beginning of the project, it can be said that the resulting device is a real success:

- It can cast battery electrodes at different thickness letting the user presetting it.
- There is a consistent thickness between the adjustments, which means that different battery electrodes cast at the same casting thickness end up being very homogeneous between each other.
- The device is able to cast at a constant speed avoiding the formation of bubbles in the top surface of the cast battery electrodes.

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- The device allows the user to choose the speed at which the battery electrode is going to be cast in the preset range of 5 – 40 mm/s.

- The initial position of the doctor blade (top of the glass slide) makes sure that the final product accounts for variability in the glass slide thickness, making sure that it does not affect in the final membrane's thickness.

- The device allows its easy cleanability as the doctor blade is finally not stationary and it can easily be removed for its cleanup and the one for the top surface of the apparatus.

- The device is able to work with the glass slide size stated at the beginning of the project: 75 x 50 x 1.5 (L x W x H).

9.2 Conclusions regarding requirements

But the resulting apparatus not only ended up achieving the project's objectives, but also met important requirements such as:

- The device can maintain the glass slide resting just after the casting process and before the solidification in the precipitation water bath. In addition, it must be stated that the required resting time was at least 300 s, but the final device is able to leave the membrane resting indefinitely following the user's will.

- The apparatus can cast a film with a casting thickness variability under the required 12%. This is due to the tight tolerance achieved in the mechanical design.

- Repeatability. The device can cast battery electrodes indefinitely as long as it is supervised, and it is given the required power.

- The final product can push the glass slide to the precipitation bath in an angle in which not only it breaks the surface tension of the nonsolvent (water) but also it makes sure that the glass slide falls upright.

- The device can be easily moved as its weight is under the required 25kg (approximately 8kg). In addition, the housing of the apparatus has been designed to allow its mobility.

- The apparatus complies with the required power limit. It only needs to be plugged to the wall as it only has 2 power terminals (5 and 12 V).

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CHAPTER 9 – CONCLUSIONS

- The device has a friendly interface allowing the user its use in an easy and intuitive manner thanks to the electronic box, which was finally implemented under the casting housing to make it more compact.
- The apparatus is automated.
- The final product has ended up being very safe thanks to the overall housing design and the code implemented in the microcontroller.
- The device complies the predefined $400 maximum budget.
- The whole apparatus design has been documented to the customers so that they can easily repeat its manufacturability or even improve it. They were pleased to see that the parts were easily interchangeable and could easily be re-machined to support a variety of glass slides.

In addition, the customers not only appreciated having complied with the friendly interface requirement, but also thanked that the apparatus made the casting process much simpler, quicker, and comfortable.

9.3 Final comments

Finally, a final comment must be made regarding the overall impact of the apparatus manufactured. As explained in the introduction and motivation of the memory, this project has been evaluated in Boston University not only for the Werner's lab customers but also for the Boston University's Mechanical Engineering Department during the whole year, and specially on the Senior Capstone Presentations that took place in Boston on the 6th of May of 2022.

The event was a unique opportunity to present to the Massachusetts scientific community all the progress made in the film casting industry. As expected, some experts in the matter attended the presentation in which all the project was explained. At the end of it, they were surprised and glad of the huge progress made, especially because this final product differentiated a lot from the other market options in these two topics:

1) The short amount of budget required to build this film casting apparatus.

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2) The implementation of a step in the process which none of the market devices was able to do: pushing the glass slide back to the precipitation bath after being cast. In this context, they suggested the protection and commercialization of this idea with the request of a patent.

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CHAPTER 10. REFERENCES

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APPENDIX A

APPENDIX A

AUTOMATED MEMBRANE CASTING APPARATUS
Workplan

Project Start: 4/10/21

TASK DESCRIPTION	PLAN START	PLAN END	TYPE
1st SEMESTER	4/10/21	20/12/21	
1.Conceptual design: objectives & constraints	4/10/21	14/10/21	B
2.Proof of concept prototype	11/10/21	18/10/21	B
3.Decide on moving object & reference	18/10/21	25/10/21	B
4.Tension doctor blade to reference/hold down glass slide	18/10/21	1/11/21	B
5.CAD of main structure and 3D print it	25/10/21	9/11/21	B
6.Manually moving prototype	9/11/21	16/11/21	B
7.Solution to casting movement (constant speed)	9/11/21	23/11/21	B
8.Adapt past prototype to automated movement	23/11/21	30/11/21	B
9.Overall shape and structure of doctor blade	23/11/21	14/12/21	B
10.Solution to variation of thickness	30/11/21	14/12/21	B
11.Decide on materials and order stock	14/12/21	21/12/21	B
2nd SEMESTER	17/1/22	27/6/22	
1.Solution to drop glass slide into water	17/1/22	24/1/22	B
2.Tolerances study and check machining with EPIC	17/1/22	31/1/22	B
3.CAD of doctor blade	31/1/22	7/3/22	B
4.Electronics	31/1/22	14/3/22	
4.1 Setting movement constant speed	31/1/22	7/2/22	B
4.2 Automated direction of the movement	7/2/22	21/2/22	B
4.3 Solution to speed regulation	21/2/22	7/3/22	B
4.4 Atomated detection of movement boundaries	28/2/22	14/3/22	B
5. Doctor blade manufacturing	7/3/22	14/3/22	B
6. Blade + structure assembly	14/3/22	21/3/22	B
7. Manual testing of thickness regulator	21/3/22	28/3/22	B
8. Implementation of electronics into device	28/3/22	11/4/22	B
9.Test automated device	11/4/22	18/4/22	B
10.Optimize design + Potential improvements	18/4/22	25/4/22	B
11. Final testing with customer	25/4/22	2/5/22	B
12.Report	2/5/22	6/6/22	B

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APPENDIX B

APPENDIX   B

Notes:
- Surface finishes are in microns

10.00   40.00   10.00

$\phi 8.000^{+0.023}_{+0.015}$

13

$\phi 17.000^{+0.008}_{-0.008}$

0.03 | A

0.03 | A

UNLESS OTHERWISE SPECIFIED:	NAME: Aaron Pan	
DIMENSIONS ARE IN MILLIMETERS TOLERANCES:	DATE: 2/16/22	
	EMAIL: apan18@bu.edu	
X ± 2.5	CELL: 6178006898	TITLE:
.X ± 0.25	BU-ID: U68590138	
.XX ± 0.13		Casting Cylinder V2
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5-2018	COMMENTS:	
MATERIAL: 316L Stainless Steel		SIZE B DWG. NO. REV
UNITS: MILLIMETERS		
DO NOT SCALE DRAWING		SCALE: 2:1 WEIGHT: SHEET 1 OF 1

SOLIDWORKS Educational Product. For Instructional Use Only.

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APPENDIX C

APPENDIX C

Notes:
- 2 of these are made for the assembly

Casting Adjustment Block

NAME: Aaron Pan
DATE: 2/24/22
EMAIL: apan18@bu.edu
CELL: 6178006898
BU-ID: U68590138

MATERIAL: 6061-T6
UNITS: MILLIMETERS

SCALE: 2:1   SHEET 1 OF 1

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APPENDIX D

APPENDIX D

APPENDIX E

APPENDIX F

Date	Item Name	Quantity	Link	Total Price
11/13/21	Stepper motor controller w microstepping	5	https://www.amazon.com/BIQU-Compatible-:	$10.99
11/22/21	Corrosion-Resistant 316/316L Stainless Steel Rod (3/4in diameter and 1/2 foot length)	1	https://www.mcmaster.com/89325K17/	$12.20
11/23/21	Multipurpose 6061 Aluminum (7/16in Thick, 6in x 6in)	1	https://www.mcmaster.com/9246K483/	$16.92
1/26/22	3D Printer Part End Stop Limit Switch	5	https://www.amazon.com/gp/product/B09K7	$8.99
1/2/22	LCD Display	2	https://www.amazon.com/dp/B00HJ6AFW6?	$9.19
2/14/22	Socket Head Cap Screw Assortment	1	https://www.amazon.com/dp/B0777HNR67?	$22.99
2/15/22	M3 Heat Set Inserts w/ Soldering Iron Tip	30	https://www.amazon.com/Insert-Inserts-Com	$15.95
2/22/22	M5 Heat Set Inserts	50	https://www.amazon.com/dp/B08T9W17CR?	$12.99
3/15/22	Moisture resistant HDPE sheet (12"*24"*1/2")	1	https://www.mcmaster.com/8619K472/	$27.81
3/28/22	TMC2209 V2.0 Stepper Motor Driver	5	https://www.amazon.com/gp/product/B09BK	$19.99
3/29/22	2pcs RV24YN20S 10K Potentiometer	2	https://www.amazon.com/gp/product/B0795	$11.99
4/13/22	Plastic Project Boxes for Electronics	1	https://www.amazon.com/dp/B09BJCP428/re	$33.99
4/14/22	M5-0.8 x 12mm Socket Head Cap Screws	1	https://www.amazon.com/gp/product/B07L8	$8.49
4/23/22	Moisture resistant HDPE sheet (12"*24"*1/2")	1	https://www.mcmaster.com/8619K472/	$27.81
4/24/22	Polypropylene Sheet 12" x 24" x 1/4", Semi-Clear White	1	https://www.mcmaster.com/8742K235/	$29.52
4/30/22	M3 Socket Head Cap Screw Assortment	1	https://www.amazon.com/gp/product/B07CX	$11.99
5/1/22	M5 Socket Head Cap Screw Assortment	1	https://www.amazon.com/gp/product/B07SB	$8.99
5/2/22	M3 Heat Set Inserts	100	https://www.amazon.com/gp/product/B08T7	$14.39
5/3/22	M5 Heat Set Inserts	50	https://www.amazon.com/gp/product/B08T9	$12.99
6/5/22	Moisture resistant HDPE sheet (12"*24"*1/2")	1	https://www.mcmaster.com/8619K472/	$27.81
6/5/22	Multipurpose 6061 Aluminum (7/16in Thick, 6in x 6in)	1	https://www.mcmaster.com/9246k483/	$16.92
6/5/22	Stainless Steel Feeler Gauge	1	https://www.amazon.com/dp/B07XPD9L1C?p	$14.99
6/5/22	5.5 x 2.1 mm DC Power Jack Socket	6	https://www.amazon.com/dp/B08SJM2G52?	$10.90
6/5/22	Double head Engraving Marking pen	2	https://www.amazon.com/dp/B07SBGQ7WW	$7.99