ECOLE POLYTECHNIQUE

BIO302 INTERNSHIP

Development of a mechanical actuator for an organ-on-a-chip platform

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1 Introduction

For the monitoring of many pathologies, it is essential to develop quantitative assays to probe complex biological processes from the molecular to the organ scale. This is particularly true for rapidly progressing glomerulonephritis (RPGN) and segmental and focal hyalinosis (SFH), which can cause dedifferentiation and uncontrolled migration of specialized cells through a complex interplay between different molecular cues. The lack of devices to probe cellular and molecular responses in a relevant in-vitro environment has so far hindered the mechanistic understanding of this phenomenon.

Based on the microsystem already developed in the laboratory for the co-culture of renal cells recapitulating a renal glomerulus (Figure 1.1), I will develop a mechanical actuation system that allows the recirculation of the culture medium in the system in a permanent manner.

The mechanical actuation system will be realized from parts designed and 3D printed in the laboratory as well as an integrated electronic control system based on arduino and servomotors. The system will have to satisfy certain requirements; portability, waterproofness and size related to the use in sterile cell culture environment.

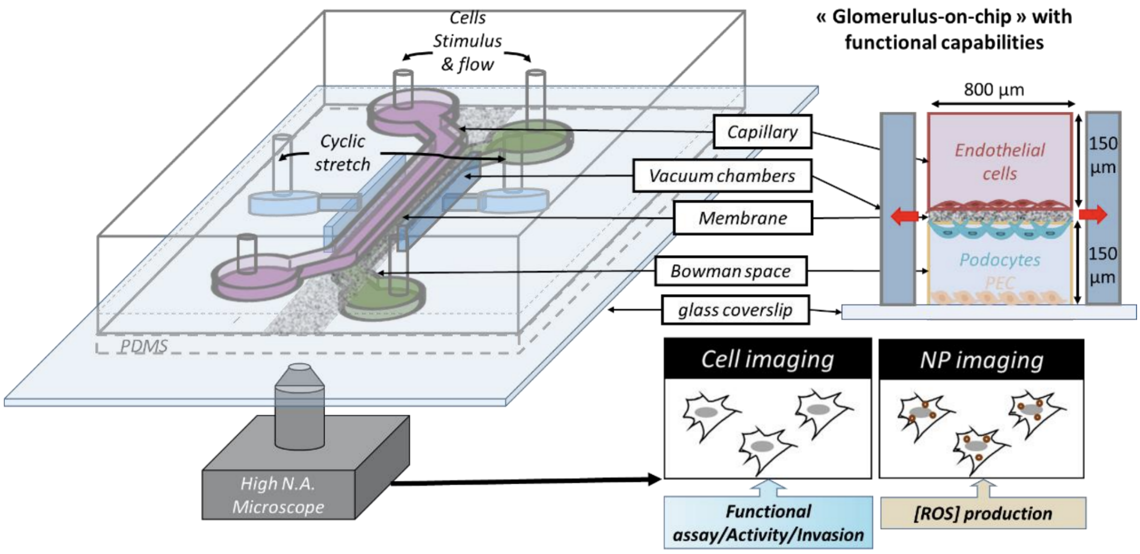


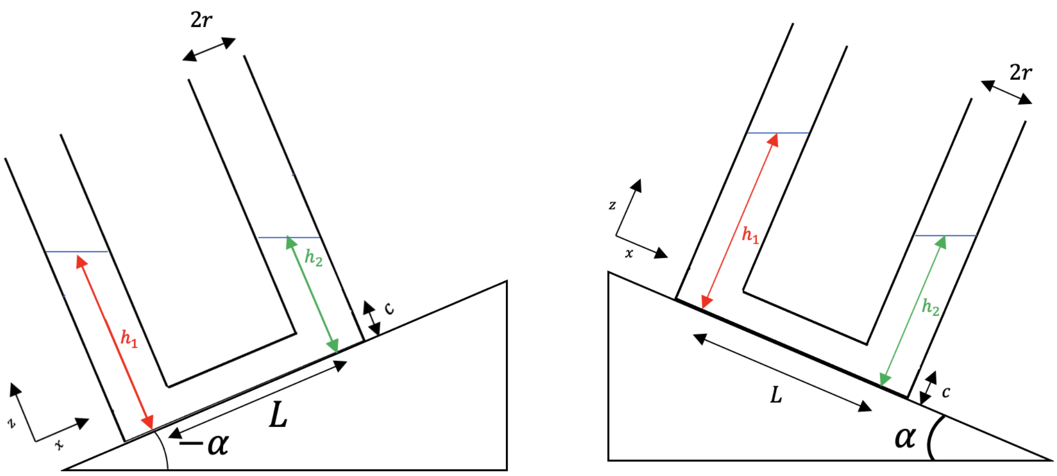
FIGURE 1.1: Microfluidic system used to recapitulate the functional organization of the renal glomerulus.

2 Conceptual Design

2.1 Defining the problem

We want to recirculate the culture medium in a permanent manner in the system. So, we thought of building an oscillator that will perturb the hydrostatic equilibrium by rotating the system between an angle α and $-\alpha$.

After reaching the hydrostatic equilibrium at $-\alpha$, we put the system at an angle α (Figure 2.1). We have initially at $t = 0$, that $h_1(0) = h_0 + L\tan(\alpha)$ and $h_2(0) = h_0$. We define $H(t) = (h_1(t) + L\tan(\alpha) - h_2(t))\cos(\alpha)$. Using the geometry of the problem, we get that: $H(0) = 2L\sin(\alpha)$.



(A) System at $-\alpha$ at hydrostatic equilibrium

(B) System at α at $t = 0$

FIGURE 2.1: System before and after the rotation of the plate by angle 2α.

After a given time T, the system will reach a new hydrostatic equilibrium, where

$$h_1(T) = h_0 \text{ and } h_2(T) = h_0 + L\tan(\alpha)$$

Then, the displaced volume will be:

$$V = \pi r^2(h_2(T) - h_2(0)) = \pi r^2 L\tan(\alpha) \approx \pi \times 2.5^2 \times 7.5\tan(18^\circ) = 48\text{mm}^3 = 48\mu\text{L}$$

2.2 Derivation of the equations

The difference of pressure between the first and second cylinder drives the fluid. We have that the pressure difference is:

$$\Delta P(t) = \rho g H(t)$$

This generate a Poiseuille flow, with flow rate:

$$Q = \frac{bc^3 \Delta P}{12\eta L}$$

By the conservation of the flow rate, we have that the flow rate in the two cylinders is equal to the flow rate in the linking part, then:

$$Q = Q_2 = Q_1, \text{ with } Q_1 = -\pi r^2 \frac{dh_1}{dt} \text{ and } Q_2 = \pi r^2 \frac{dh_2}{dt}$$

Then,

$$Q_1 + Q_2 = 2Q$$

Then,

$$\pi r^2 \frac{d(h_2 - h_1)}{dt} = \frac{bc^3 \Delta P}{6\eta L}$$

Then,

$$-\pi r^2 \frac{dH}{dt} = \frac{bc^3 \rho g H \cos(\alpha)}{12\eta L}$$

Then,

$$\frac{dH}{dt} = -\frac{bc^3 \rho g H \cos(\alpha)}{6\pi r^2 \eta L}$$

Then,

$$\frac{dH}{H} = -\frac{bc^3 \rho g \cos(\alpha)}{6\pi r^2 \eta L} dt$$

Then,

$$H(t) = H(0) \exp\left(-\frac{bc^3 \rho g \cos(\alpha)}{6\pi r^2 \eta L} t\right)$$

Then,

$$H(t) = 2L\sin(\alpha) \exp\left(-\frac{bc^3 \rho g \cos(\alpha)}{6\pi r^2 \eta L} t\right)$$

We obtain the characteristic time τ:

$$\tau = \frac{6\pi r^2 \eta L}{bc^3 \rho g \cos(\alpha)}$$

At $T' = 5\tau, H(T') \approx 0$.
For $r = 2.5$ mm, $\eta = 10^{-3}$Pa s, $L = 7.5$ mm, $b = 800\ \mu$m, $c = 100\ \mu$m, $\rho = 10^3$ kgm^{-3}, we get that:

$$T' = \frac{30\pi r^2 \eta L}{bc^3 \rho g \cos(\alpha)} \approx \frac{30\pi \times 2.5^2 \times 10^{-6} \times 10^{-3} \times 7.5 \times 10^{-3}}{800 \times 10^{-6} \times 10^{-12} \times 10^3 \times 10 \cos(18^\circ)} \approx 580s$$

Thus, after 580 seconds, the hydrostatic equilibrium is reached.

Now, we plot this characteristic time as a function of different parameters:

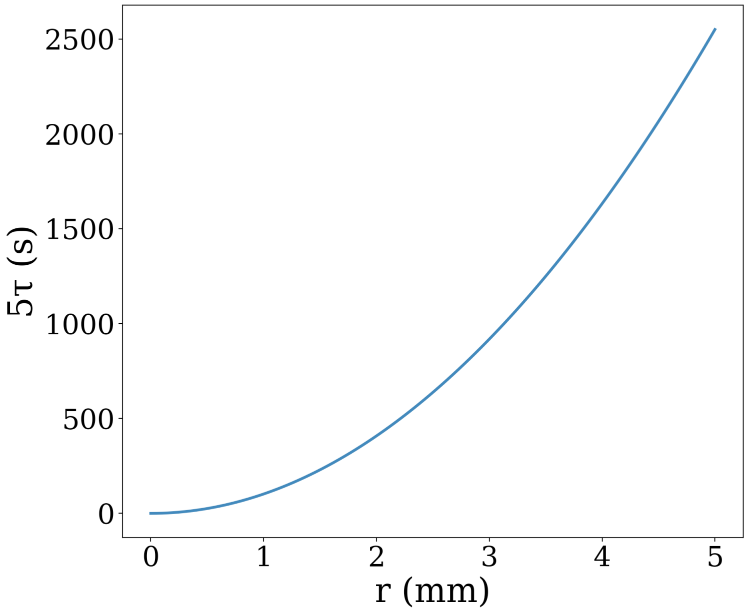


FIGURE 2.2: 5τ as a function of the radius r of the tube for $\alpha = \frac{\pi}{6}$.

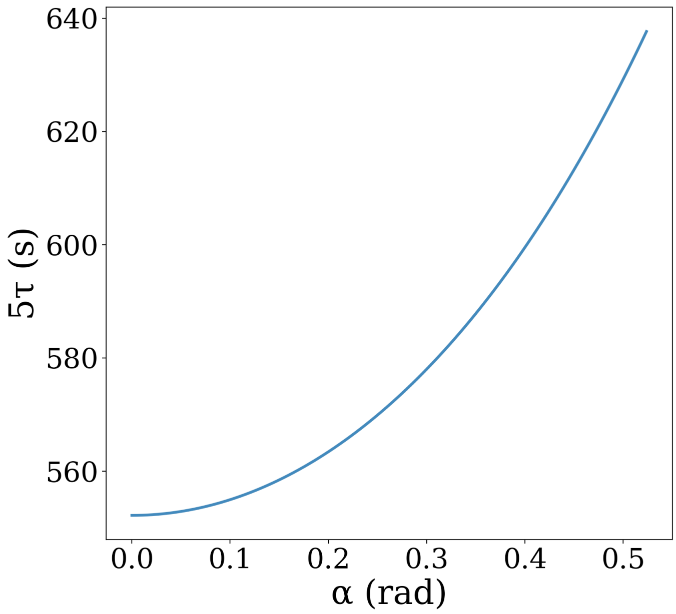


FIGURE 2.3: 5τ as a function of α for $r = 2.5$mm.

3 Building a prototype

3.1 CAD Drawings

Now, we design an oscillator that would allow us to perturb the hydrostatic equilibrium as indicated above. We design the parts on SolidWorks, before 3D printing and assembling them. Here are the drawings of the parts used:

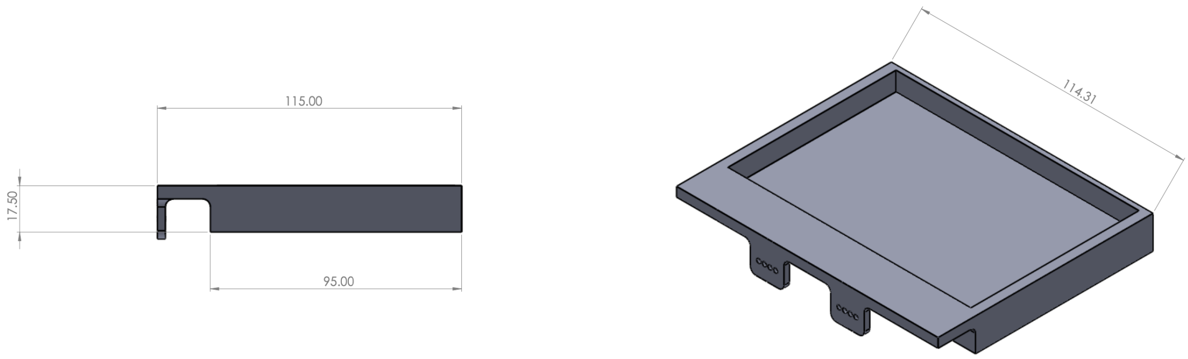


FIGURE 3.1: CAD Drawing of the oscillating plate.

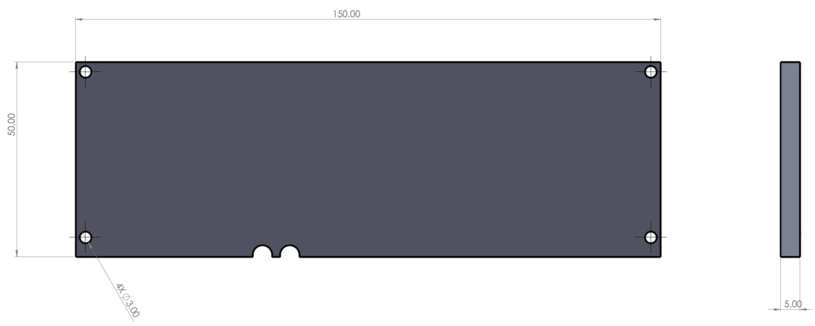


FIGURE 3.2: CAD Drawing of the door

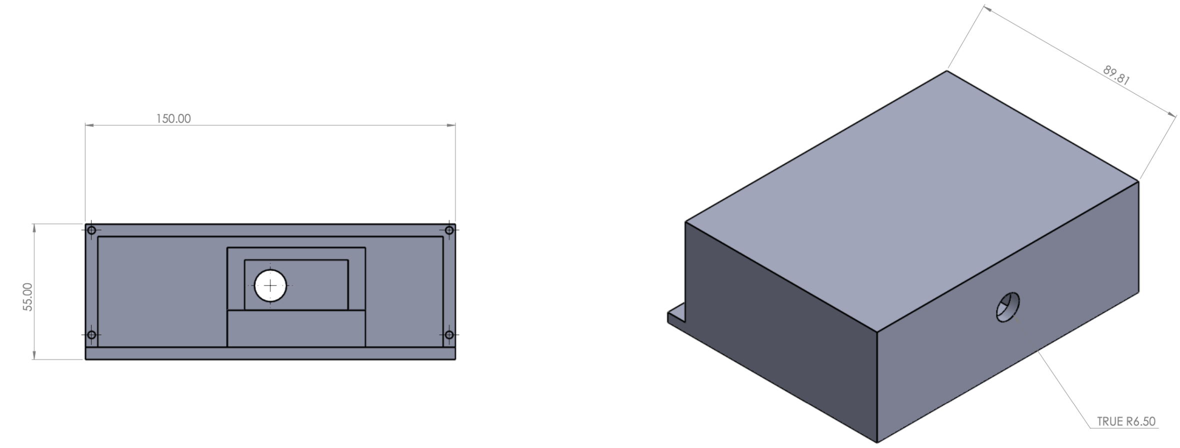
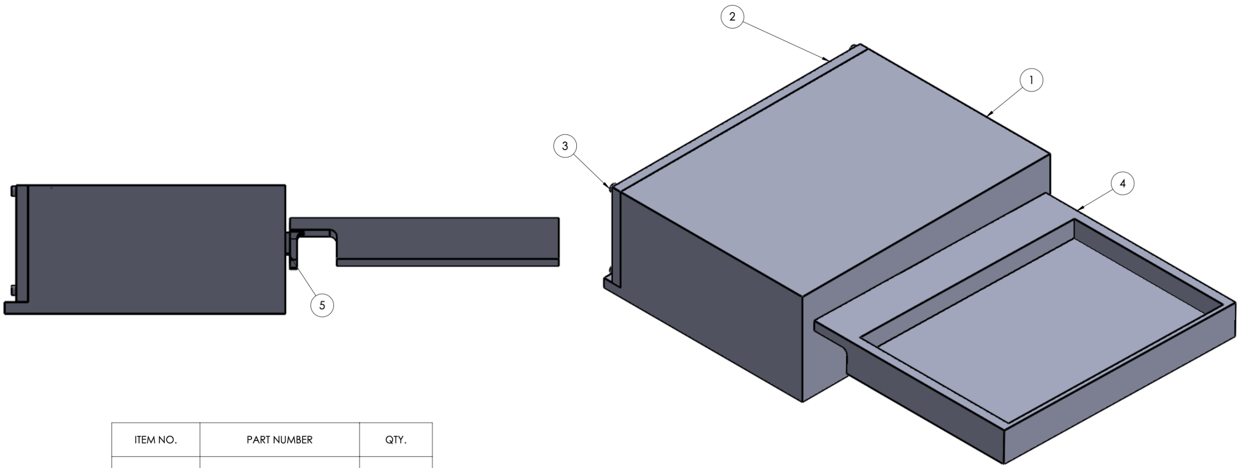


FIGURE 3.3: CAD Drawing of the house of the servomotor.

And here is the drawing of the assembly as well as the table of material used:



ITEM NO.	PART NUMBER	QTY.
1	MOTOR HOUSE	1
2	DOOR	1
3	BOLT	4
4	OSCILLATING PLATE	1
5	LINKING PART BETWEEN PLATE AND MOTOR	1

FIGURE 3.4: CAD Drawing of the assembly, with the table of material.

3.2 Electronics and programming

Now we use a waterproof servomotor (sg90) that we connect to an Arduino UNO using the circuit shown in Figure 3.1, to realize the oscillations of the plate. The code can be found in "main.ino".

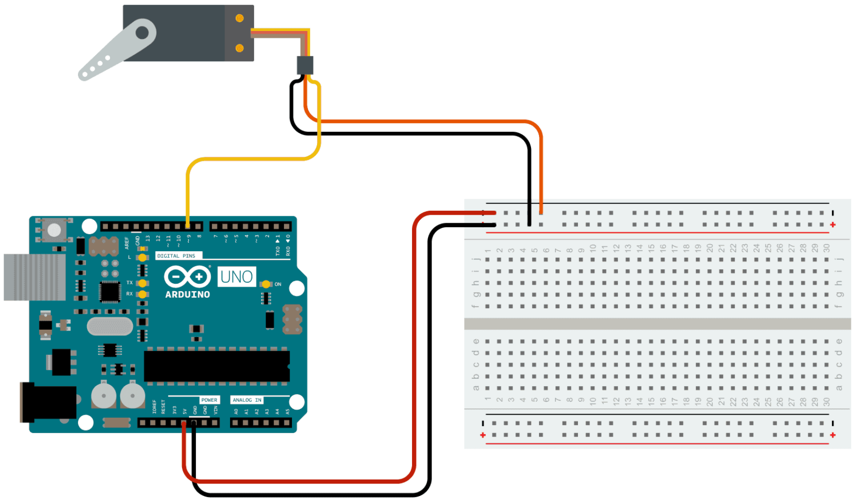


FIGURE 3.5: Servo Sweep circuit

We activate the motor and control the oscillation period using a touch screen (4d systems). We also print the number of oscillations done on that screen. The code can be found in "main.ino".

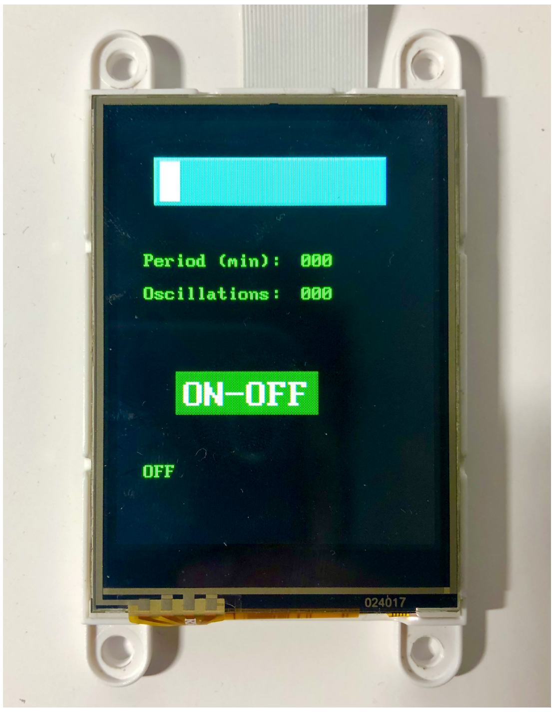


FIGURE 3.6: Touch Screen

4 Final Product

After assembling all the parts together and adding adding the electronics we get the following final product which is an oscillator that will stay stationary for a given period of time controlled by the touch screen.

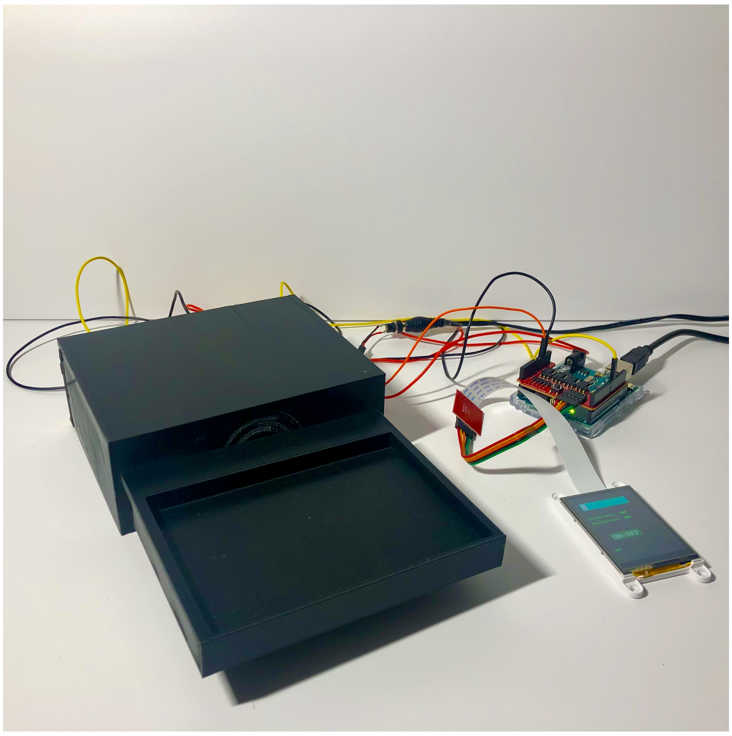


FIGURE 4.1: Final product.

Bibliography

[1] Arduino documentation. [Online] Available: https://docs.arduino.cc/learn/electronics/servo-motors [Accessed: 08/06/2022]

[2] Fluid Mechanics, 8th Edition, Frank M. White, 2016