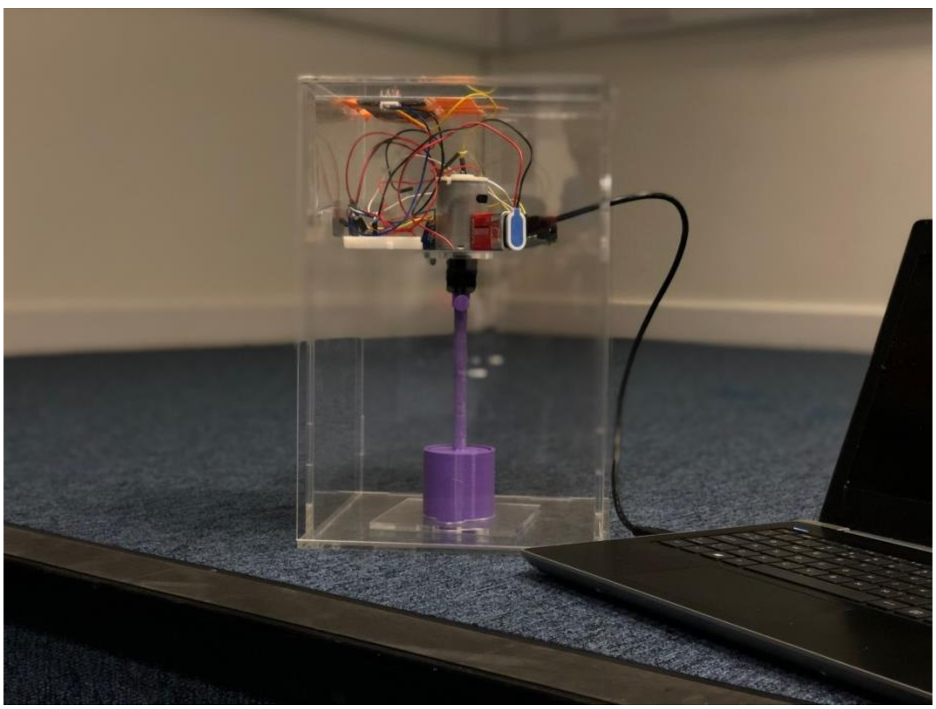
# FINAL DESIGN REPORT

**JUNE 3RD, 2021**



# COMPANY 3: IMNOVATION
# TITLE OF DESIGN: IMNOMETER

# Imnovation

Emir Ziyal
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SIDDHARTH

## **Introduction**

As a team of 10 imnovative minds from Imperial College London, Imnovation is proud to finally present you the groundbreaking project: the "Imnometer." Fluid mechanics is one of the most important concepts in the science world and has lots of uses in our daily lives, but the two machines generally used, viscometers and rheometers, can be hard to get a hand on. Our team is here to solve this by introducing the Imnometer, a cheap, portable, precise and accurate viscometer alternative that is going to leave its mark in the academia. We have tried to approach the problem of inaccessibility to viscometers with great care and creativity, hoping to bring you the best project possible.

To briefly explain our thought process, we first examined the different types of rheometers and viscometers. We saw that rheometers are much more advanced and can control and measure a wider range of parameters; however, they are also significantly more expensive. Viscometers on the other hand, measure properties with much less characterization. Their main advantage is that it allows portability to some extent. [1] As a team, we are aiming to increase the portability to help with remote testing and experiments while still being as accurate and precise as a regular viscometer.

There are types of viscometers as well. Since we pursued a versatile rheology device, we have successfully implemented the Imnometer to switch between 3 of the most used rotational types: parallel plates, cone-and-plate and bob-and-cup viscometers. To achieve this, our viscometer has interchangeable parts to change between the three types. Parallel plate viscometers are the most precise type of rotational viscometers; however, they are sensitive, making it hard to have accurate reading in some cases. For the second type, cone-and-plate, they are precise while being less sensitive; however, they have the tendency to wear out easier and are usually better for non-Newtonian fluids. So, our viscometer will be able to work with all fluids, while also allowing the user to make changes within the device to have better measurement.

Our viscometer's circuit is connected to an Arduino Uno powered up by a computer. But the most important element in the circuit is the Nextion touch screen that is being used. Through it, the user will be able to select the mechanism being used, and will be able to see both the final graph and the viscosity value on the screen. The screen is also perfectly compatible with the Arduino Uno inside, making it easy to work with. In general, it will be extremely convenient to take the measurements.

Although our innovative vision and the Imnometer's versatility and affordability will set us apart from the competitors, another thing we value greatly is aesthetics. The design resembles a box, following a minimalistic approach. This design also allows easier portability and maintenance. The Imnometer is mostly transparent, making it even more minimalistic. The transparency also provides some practicality by allowing the mechanisms to be observed while the measurements are being taken. The top part of the design will be coloured purple to both give it a more refreshing look and to represent our company's signature colour: purple. It will prevent all the circuitry to be seen, making it more pleasant to look at.

Also to briefly talk about the materials used in the design, 5mm clear cast acrylic was used for the box and PLA was used for the components. Although they may not be the most environmentally materials, they boost the affordability aspect of the product and are still recyclable. More information about this can be found later on in the sustainability report.

All in all, Imnovation has brought a device ready to change the science world. The impossible combination of affordability, accuracy, precision, aesthetics and portability have been made true in this revolutionary project. The 10 bright minds working in the team are more than pleased to present the final version of our project and are looking forward to start mass producing the device, hoping that every school or college will be able to access this device to educate the youth and help develop imnovative minds.

# SUBSYSTEM 1: CALCULATIONS & USER INTERFACE

**Karen Pacho Dominguez – Chief of Production**
**Siddharth Puri – Chief of Sustainability**
**Daniel Huang – 3D Printing Engineer**

Imnovation

# MEET THE SUBSYSTEM

## Karen Pacho Dominguez
## Chief of Production

I contributed to the coding for both the Arduino and the nextion. I integrated the different calculations codes into the initial keypad selection interface which I and other members wrote and were eventually incorporated to the main code. I designed the nextion interface and coded its functionality. I sketched some of the mechanisms on Solidworks as well as contributed to deciding on modifications to the imnometer to solve the problems we encountered during the project. I also kept the production record.

## Siddharth Puri
## Chief of Sustainability

Initially I worked on the assembly of the prototype- creating the makeshift spindles, building the viscometer case using cardboard, and cross checking the dimensions to make sure that they were feasible. After the prototype phase I worked on coding the Nextion touchscreen. I helped link the nextion and Arduino code and ensure that the graphs were plotted correctly. As the chief of sustainability, I helped make the decision to make the viscometer smaller which would allow for significant material savings as well as allow for a reduced carbon footprint. During prototyping I ensured that we used recycled items such as old cardboard boxes.

## Daniel Huang
## 3D Printing Engineer

In the early phase, I took part in the inital research and organisation in coding and calculation to help the company to gain a good understanding about the overall mechanism. As a 3D printing engineer, I also contributed in the techincal drawing and 3D printing document preparation in the final design.

## Calculating Viscosity

Viscosity η is a ratio of the shear stress $\tau$ against the shear rate to $\dot{\gamma}$ which can be calculated by different geometries such as the parallel plate, coaxial cylinders, and cone and plate mechanisms used in the Imnometer. Once the mechanism and fluid are in place, there will be a torque required to match the set rotational speed which is used to calculate shear rate. Since the current is directly related to the torque by equation 1, the change in current will be used to calculate the torque, where the *I* is the current, *V* is the voltage and *E* is the efficiency of the motor:[2]

$$\text{Torque}= \frac{I \cdot V \cdot E \cdot 60}{rpm \cdot 2\pi} \qquad (\textit{Eq. 1})$$

For the parallel plate, given the constant gap distance, constant plate radius, fixed voltage or current (whichever is easier to maintain constant), and rotational speed Ω that are under our control, the output of the previous equation can be substituted in the following equation to calculate the torque of the rotating disk:[3]

$$M = \int_0^R \tau(r) \cdot r \cdot 2\pi r \cdot dr \qquad (\textit{Eq. 2})$$

As the values of *M* and Ω have been defined, the following equation can then be used to calculate the viscosity η for that shear rate $\dot{\gamma}$(r) (which is equal to $\dot{\gamma}(r) = \frac{r\Omega}{H}$), where *H* is the gap between plates:[3]

$$\eta = \frac{2MH}{\pi R^4 \Omega} = \frac{2M}{\pi R^3 \, \dot{\gamma}_R} \qquad (\textit{Eq. 3})$$

Although the last two equations[3] are specific to the parallel plate geometry, all geometries rely on the rotational speed and the torque (defined by the current and voltage) of the motor both of which are measured by the Arduino. For completeness, the other equations used to calculate viscosity in the Imnometer are below. Equation 4 is for the cone and plate mechanism where α is the angle of the cone.

$$\eta = \frac{3M\alpha}{2\pi R^3 \Omega} \qquad (\textit{Eq. 4})$$

$$\eta = \frac{\tau\,(\mathrm{r})}{\dot{\gamma}_R} = \frac{M}{2\pi R^2 \mathrm{L}} \div \frac{2\Omega}{n\left[1-\left(\frac{\mathrm{R}_i}{\mathrm{R}_o}\right)^{\frac{2}{n}}\right]} \qquad (\textit{Eq. 5.1})$$

*Where $R_i$ is the radius of the inner cylinder and $R_o$ is the radius of the outer cylinder measure from the inside wall to its center, and:*

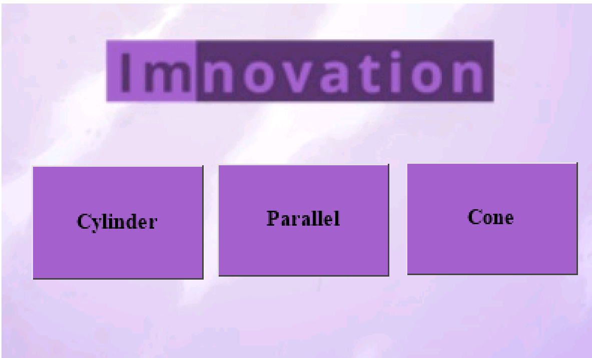
$$\frac{d \ln M}{d \ln \Omega} = n \qquad (\textit{Eq. 5.2})$$

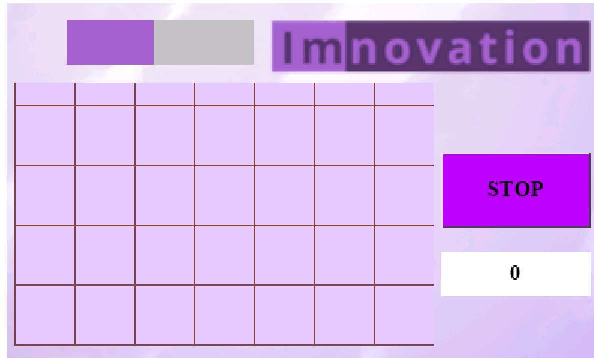
Ideally, the viscosity would not change with different rotational speeds and torques because only Newtonian Fluids were considered in the first place. However, it is impossible to obtain experimental values that do not deviate from a perfect linear relationship due to the imprecision introduced by random errors. Therefore, linear regression line was applied during calculations for the value of viscosity.

## Nextion Interface:

The Nextion screen was chosen as the front-end user interface since it is an easy to use touchscreen which can be run from an Arduino board. The Nextion Editor app uses a drag-and-drop style of coding which makes it easy to organise different front-end functionalities such as buttons and progress bars. The Nextion editor allows the use of hexadecimal code which can code basic loops and timer functions intrinsically without the help of an arduino IDE code. This allows us to code objects like progress bars directly from the Nextion editor. Several pre-published libraries exist which allow us to code the Nextion touchscreen from the Arduino IDE. Coding through the Arduino IDE allows us to perform more complicated tasks and use objects like lists and floating-point variables. Designing the graphics of the features of the user interface was a quick and efficient step of the creating GUI for the Imnometer.

We produced the following interface:




**Figures 1 & 2.** Home screen of Nextion LCD screen (left) and page to plot viscosity for corresponding mechanism (right).

When the power source is connected to the Arduino board, the Nextion screen turns on and displays the home page. The home page provides the customer with 3 options in the form of buttons. The leftmost button displays "Cylinder" (for the coaxial cylinder mechanism), the central button displays "Parallel" (for the parallel plate mechanism), while the rightmost button displays "Cone"(for the cone and plate mechanism). Based on the fluid that is being measured, the customer has to manually change the mechanism to the appropriate one and then click on the button which corresponds to that particular mechanism to start the viscometer motor. Once the button is pressed, the motor starts and the viscosity calculations are performed. On the front end, the screen changes to another page which displays a graph representing the viscosity data calculated for that fluid. Next to the graph there is a "Stop" button which prevents the motor and the code from running and takes the customer back to the home page.

The graph plotted on the Nextion is a 1-axis graph. To plot values on this type of graph, a timer is set which continually adds values to the graphing variable (sys0) from the values calculated by the arduino code.

Adding functionality to these features was a considerable challenge; the syntax for coding the LCD screen is quite unique to Nextion products which was unlike any language that any company member was familiar with. Commands needed to be coded directly in the Nextion Editior, often in hexadecimals and code for the arduino had to be closely integrated to match the Nextion Editior code in order to communicate between these components of the circuit. Useful documentation out of the open source libraries available on the internet was also difficult to find for this Nextion LCD screen but there were two major sources of information.

We initially utilised a library where there was a large number of inbuilt functions and variables that initially did facilitate the coding process as the library was accessible and almost self-explanatory. However, this library heavily relied on Nextion Editor code in order to navigate between different screens and so suffered from many bugs that were incredibly laborious to solve. This library (simply called 'Nextion') also lacked the functions necessary for plotting values to a graph compatible with the nextion waveform object.

As a result, we eventually employed a second library ('EasyNextionLibrary') after much research. The documentation was much stronger for this library, but it was not as accessible to understand with our coding ability. Nevertheless, by combining these two libraries, we successfully solved the graphing issues and achieved full functionality between all the features we designed for the LCD screen user face.

When the power source is connected to the Arduino board, the Nextion screen turns on and displays the home page. The home page provides the customer with 3 options in the form of buttons. The leftmost button displays "Cylinder" (for the coaxial cylinder mechanism), the central button displays "Parallel" (for the parallel plate mechanism), while the rightmost button displays "Cone"(for the cone and plate mechanism). Based on the fluid that is being measured, the customer has to manually change the mechanism to the appropriate one and then click on the button which corresponds to that particular mechanism to start the viscometer motor. Once the button is pressed, the motor starts and the viscosity calculations are performed. On the front end, the screen changes to another page which displays a graph representing the viscosity data calculated for that fluid. Next to the graph there is a "Stop" button which prevents the motor and the code from running and takes the customer back to the home page.

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# SUBSYSTEM 2: DESIGN & ASSEMBLYING

**Amelia Hu – Chief of Engineering**
**Yifan Yu – Laser Cutting Engineer**
**Emir Ziyal - Director**
**Alberto Fantini – Chief Financial Officer**

# MEET THE SUBSYSTEM

## Amelia Hu
## Chief Engineer

Mainly responsible for the overall design in terms of 3D visualisations and technical drawings organisation in Solidworks, also took in part of 3D printing and laser cutting arrangements including material selection. Recently, the focus is adjusting the design to overcome issues in the final assembly and make it more reliable to achieve the final objective of successful operation.

## Yifan Yu
## Laser Cutting Engineer

Responsible for the document preparation of the laser cutting. In addition, assisting in the necessary design adjustments over the prototype phase and technical drawing.

Yifan Yu

## Emir Ziyal
## Director

As the director of the Project, I trie to shadow everyone and tried to be involved and help others as much as I can. I decided to volunteer as the in person 3D printer because our 3D printer was remote, so I printed all of the components done in the summer term. I also worked hard in the assembly, mainly trying to help Alberto with the manual work and trying to come up with fast solutions to the problems we faced. I also helped with the coding of the Nextion and laser cutting.

## Alberto Fantini
## Chief Financial Officer

Throughout the entirety of the project apart from carrying out the duties as Financial director I had the aim to actively participate and give as many suggestions to create and improve the design. In the beginning I actively helped in the initial concept of how the design of the machine should have been, while during the prototype and the assembly I carried out most of the manual work needed and looked for any imperfection in the design and ways to improve it.

While keeping the original ideas from the concept phase, a few changes along the production process have been made to optimise the design. The current design consists of a clear-cast PMMA cuboid case made by laser-cut parts and a series of 3D printed components. The outer case has six faces with the same thickness of 5mm for rigidness and consistency in production. The full circuit is placed above and protected from the measuring environment by an inserted plane that also is made from the same material with a thickness of 5mm. The switching mechanism was designed to serve a purpose as the connection between the operating motor and the three measuring components. The Nextion touchscreen inserts into a rectangular void to cut into the top plate.

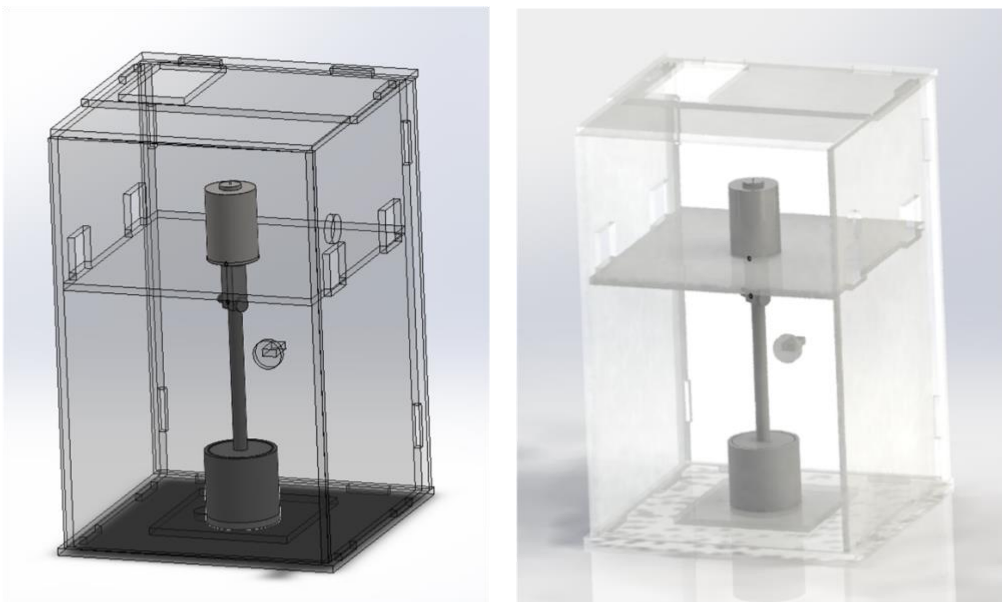

**Figure 2.** A 3D visualisation and a render of the assembly with the bob and cup mechanism.

The transparent PMMA case is smaller (200mm x 200mm x 300mm) than the one ideated in the concept design. This was to reduce the production price and improve the material usage efficiency. Subsequently, the viscometer would be more environmentally friendly and provide a lightweight user experience. The assembly includes jigsaw structures and PMMA hinges for easy construction and operation. The top face consists of 2 parts: a fixed piece which houses the touch screen, and a movable part that allows for circuit maintenance. The circuit and wiring could also be accessed from the front door. The front door is closed during operation in order to keep the inner environment constant while the viscometer is running.

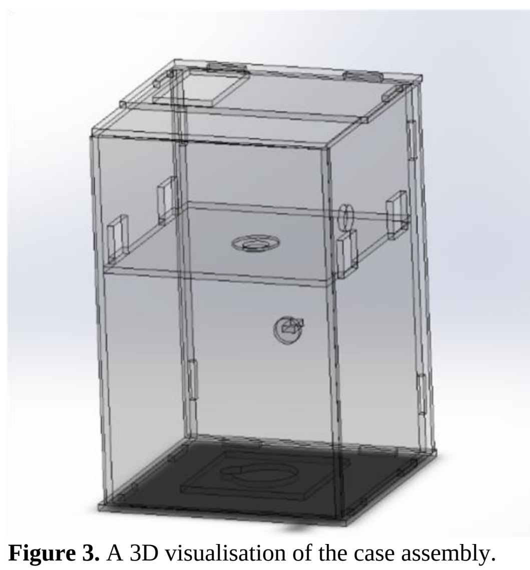

**Figure 3.** A 3D visualisation of the case assembly.

To provide a stable operating position for the motor and wiring, the inserted plate is made moveable up and down for changing the measuring unit assisted by a 30mm x 30mm rectangle cut on each side face of the case. It replaced the design of moving the whole combination of components including the motor and wirings, and a shallow cut on the plate was introduced to lock the motor in place. A switching component is connected to the motor shaft for interchangeable purpose. It has a cuboid main structure combined with two lock components to secure the spindles of different measuring components via a notch type mechanism. Two small holes were designed on one face to allow securing of spindle and motor shaft positions using M3 flat end screws. For both conveniences in 3D printing and interchanging, the switching component is split into half vertically, and two stick-hole pairs were applied in the middle for assembly.

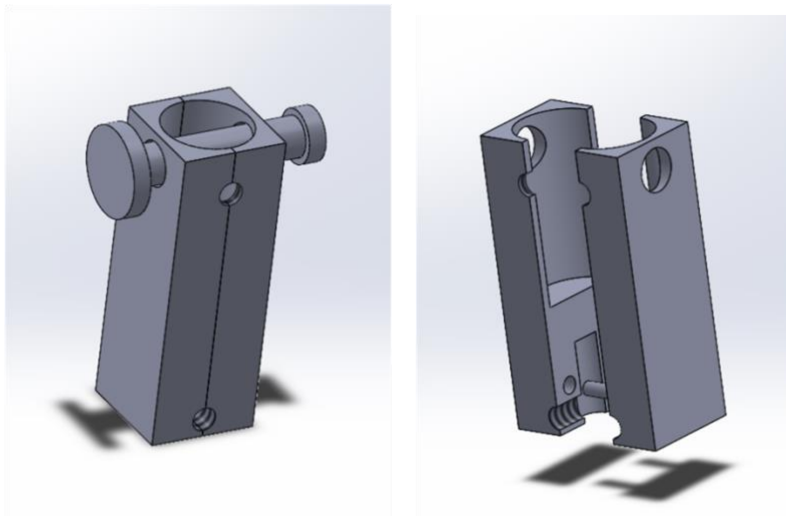

**Figure 3.** The switching component in part phase and assembly phase.

Three measuring components are available for testing different fluids. These mechanisms are the coaxial cylinder mechanism, the parallel plate mechanism, as well as the cone and plate mechanism. Each mechanism has a spindle fitted with the switching component. The coaxial cylinder mechanism consists of a cup and a bob. The parallel plates consist of a flat upper plate (attached to the spindle) and a flat bottom plate. The cone and plate mechanism is more complicated with a 4◦ angel cone with a truncated tip for a more robust measurement. These last two mechanisms have a flat bottom plate.

The gaps between the plates and the two coaxial cylinders must be kept constant to produce reliable measurements. Therefore, a stage was cut off from the remaining material after laser cutting and fixed on the bottom face of the case, stabilizing the measuring components during operation and in a central position. This was made possible by a common circular base design across all the mechanisms.

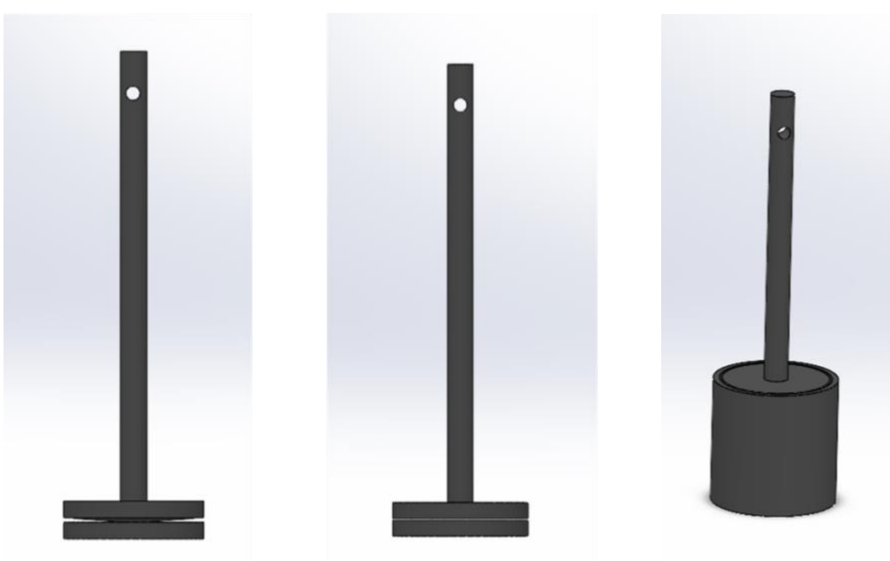

**Figure 4.** The three measuring components. From left to right, the bob and cup mechanism, the parallel plates mechanism, the cone and plate mechanism. 0.5mm gaps were used between two parts in each assembly.

Throughout the final design phase, several issues with the design of the product were identified. These problems ranged from structural ones to smaller details regarding the fitting of the mechanism. The transition from a cardboard prototype to our final visualization of the product was not easy. The prototype in fact, although it gave a general understanding of how the machine would work, was unable to give insights on possible minor issues in the design. The most noticeable one was regarding the dimension of the viscometer, but through the building and the testing of the product further smaller problems were spotted.

During the final design phase, the first obstacle encountered was regarding the laser cut sheets. Due to several imprecisions in the cuts, certain components could not be properly assembled. To overcome this, manual work of cutting and polishing the surface was done, using files, to have the correct dimensions needed to assemble the Imnometer.

The second issue identified, after having a laser-cut prototype, was that the machine was too large. The original cardboard prototype did not give a correct understanding of the real dimensions or proportions of the initial concept for the viscometer which resulted in this second prototype losing functionality due to its large volume. Tight monitoring of the budget by the Chief Financial Officer meant there were enough funds to allow for re-cutting of the sheets.

The next issue encountered during the project was regarding the switching mechanism. The 3D print of the two-piece mechanism required many adjustments using drills and files, unfortunately compromising the integrity of such important piece. Upon review, a second one-piece design was re-printed which, while more rigid, was not compatible with the overall concept of the switching mechanism of the Imnometer. After a deep analysis therefore, the company decided to return to the two-piece clasping mechanism with an updated structure that would improve its stability.

The length of the spindles was another issue that afflicted the switching mechanism. The absolute height of the spindles was too long to allow for the necessary gaps between surface where the fluid would be placed. Two solutions were adopted to fix this issue: one came by giving the possibility to the user to move vertically the middle platform where the motor is placed through new laser-cuts; the second was cutting the spindles and redrilling holes.

Overall, the company undertook many thorough revisions on the design from initial concept to the final product all with the aim to producing the most cost effective, yet user friendly design as possible. As a result, Imnovation proudly presents our product.

Imnovation

# SUBSYSTEM 3: CODING

**Younes Moustiri – Chief of Automation and Control**
**Anne Sophie Korotov – Deputy Director**
**Natalie Wu – Deputy Chief of Engineer**

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# MEET THE SUBSYSTEM

## Younes Moustiri
## Chief of Automation and Control

I wrote the code that measures the RPM and current to calculate viscosity for the different mechanisms with the subgroup. I created a schematic of the circuit and ensured the entire code flowed properly and that any problems that were encountered were solved.

## Natalie Wu
## Deputy Chief of Engineer

I worked on the internal wiring and contributed to the code that measures the RPM and current to calculate viscosity. I incorporated the different equations into the code in order to accurately calculate the final viscosity values.

## Anne Sophie Korotov
## Deputy Director

My contributions were mainly to the coding subgroup. During the concept design phase I helped with the research for the circuitry and helped with decisions like whether our code should be written in python or Arduino C and which motor should be used. I also helped with the coding of the equations.
During the prototype phase I helped building the prototype out of cardboard and assemble the circuit.
In the final design phase, I helped doing the research for the Nextion code, as well as trying to write code for the linear regression, and helped with brainstorming solutions for last minute problems that we had with the design.
Lastly, I contributed majorly to writing the concept and final design report, as well as the letter.

Our goal was to build a functional circuit composed of a motor generating a torque, that will then measure the viscosity of the liquid. This involves measuring the power after the insertion of the mechanism into the water, as well as measurement of the rotational speed of the motor, using an IR sensor. The power can be calculated using a voltage and a current sensor. Further, the group had to calculate the viscosity using the data obtained from the measurements. The calculations differ depending on the mechanisms of measurement used. Plotting the shear rate against the shear strain was not possible, instead calculations were performed.

```
void trigger1(){ // Parallel plate
  trigger = 1;}
void trigger2( ) {// Cone and plate
  trigger = 2;}
void trigger3() {// coaxial cylinder
   trigger = 3;}     // Nextion triggers functions to chose the mechanisms
```

As explained in subsystem 1, upon starting the Nextion, the user will be able to choose between the three different mechanisms. These triggers are functions that run when different buttons are pressed on the Nextion. A value is assigned to the trigger variable, which dictates the equations used to calculate the viscosity. These calculations are executed after the RPM data is gathered from the motor; thus, this is what was focused on first.

An important consideration in our subgroup was the control and measurement of the rotational speed of the motor, since it plays a big role in the accuracy of our measurements. The RPM is measured across 7 speeds. Every 12 seconds, the speed of the motor will change, and the RPM and current will be measured for that speed. Afterwards, each set of RPM and current values would be used to calculate a viscosity for which an average will be taken for the final value.

In order to keep track with the time, a variable would take the value of millis() function at the start of the loop which would return the number of milliseconds the sketch has been running since the last reset. Some of the difficulties encountered included the set-up of the timer with the initial methods we tried, for example when using the Timer.h library or using delay. These functions interrupted the code and therefore the measurements. In the end, we used the millis() function which isn't affected by delays and would give accurate time.

To measure the RPM, the IR sensor detects a change whenever the edge of the half plate passes the sensor and will add 1 to the variable rev. At first, a black strip was going to be attached to the spindle and the idea was for the IR sensor to detect the black strip whenever it passed by. However, a strip was simply too small for the IR sensor to detect at the speed that the motor was spinning. We tried to make the sensor more sensitive but then there was a lot of noise in the data and therefore was not useful or accurate. In the end, we coded our own function where if the IR sensor detected a change, it would add an increment to the variable rev to count the number of revolutions.

```
  newWave = digitalRead(sensor);
}
if (oldWave != newWave) {
  rev = rev + 1;
  Serial.print(rev);
  Serial.println(" revs");
}
oldWave = newWave;
delay(1);
```

Above is the function for detecting the change to record the revolutions. The RPM is then calculated from the revolutions per 12 seconds. The sensor will detect two changes per revolution, which is considered in the calculations.

To calculate the viscosity, the change in power must be measured. This is done by measuring the current and voltage supplied to the motor. The current is measured with the ACS712 current sensor with the function below. The sensor uses indirect current sensing from the magnetic field that is generated when current flows through the sensor, which is found using the Hall effect sensor. The voltage that is proportional to the magnetic field is then used to measure the current. The difficulties for this section of the code were that there were fluctuations in the current readings as the sensor was so sensitive that a tiny change would affect the reading. To minimise the error in the values, we increased the readings we took for the current so that there is less error.

```
for(int i = 0; i < 10000; i++){
average = average + (.0264 * analogRead(A0) -13.51) / 10000;
delay(1);
```

Regarding the motor, the speed of the motor changes with the code below, with s being the index of the list speeds ( int speeds[] = {255, 230, 205, 180, 155, 130, 105, 80} ), declared at the start of the code. The speed value is sent to the PWM (Pulse width modulation) pin and the power is controlled over a MOSFET with PWM. This means that the power to the motor is regulated to give the different speeds. The difficulties with getting the motor code to work was that it was difficult to get the motor to work at low RPMs, and still maintain enough torque. In response to the problem, the speeds that we now use are a compromise where they are low enough for the measurements but high enough so that there is enough torque for it to keep spinning.

```
analogWrite(PWM_PIN,speeds[s]);
```

One of the main challenges was controlling the Arduino code so that only the part of the void loop that is needed runs. This problem was solved by assigning variables and using if statements that increment when specific parts of the code run. When these variables take certain values, it renders parts of the code null, and thus would not run for a certain number of cycles of the void loop. Below is an example of how this solution was implemented. If t is divisible by 2 then then the if statement is null. If it is not divisible by 2 then the if statement is true and the code runs, but t is incremented so that this part of the code does not run when it does not need to in the next loop cycles until t is incremented by 1 elsewhere in the code.

```
if (t%2 == 1){ // when t is not divisble by 2, this code is needed
  t = t +1; // t is incremented by 1 so that only the code that needs to run in the next loop runs
```

Below the equations that are used to calculate the viscosity.

```
  if (t >= 14){ //After all the RPMs and average currents are measured the code before is not needed
    //and the equations are only applicable after all the RPMs and average currents have been measured
    if (trigger == 1){
    for(int p = 0; p < 8 ; p++)
 {
    float PlateRadius = 0.025; // convert from mm
    float V = (speeds[p]/255)*9; // PWM voltage
    float I = allCurrents[p];
    float RPMc = RPMs[p]; //sets the variables for the calculations
    float E = 1;
    float torque = (I*V * E *60)/(RPMc *2*M_PI);
    float M = torque * 2* M_PI ; // torque * geometry
    float Omega = RPMc * 0.10472; // first value is rpm but second converts to
    //to rad/s , rpm input from ir sensor since its real time rotation
    float Gap = 0.005 ;// convert from mm gap between plates max is 5mm
    float R4 = pow(PlateRadius,4)* pow(0.001,4);
    viscosity[p] = (2*M*Gap)/(M_PI*R4*Omega);
```

In this segment of code above, there is another example where t is used. When t is greater or equal to 14, all the measurements of the RPM and the current for the different PWM values have been recorded. However, to stop the calculations from occurring during the measurements of RPMs and currents an if statement is used. The lists that contain the current and RPM are traversed in the for loop and are used to calculate a list of corresponding viscosities. First the Torque and Ω are calculated, then these are used to calculate the viscosity. Since this code only occurs if the first trigger (parallel plate) was pressed.

The last part of the code was implementing the reset function at the end of the code so the readings would reset, and the user would be able to choose another mechanism to use to measure the viscosity. During research, there were a few options to reset the code but we chose the method where we write a reset function and whenever the measurements and calculations are done the reset function would be called. The code was combined with the code from the subgroup that coded the Nextion LCD.

Further, we focused on building a circuit. Below is a schematic for the electrical wiring. The IR sensor and the current supply are both supplied power from the Arduino, which is connected to a power supply. The IR sensor is connected to the digital pin 3, and the current sensor is connected to analog pin 0. The motor is powered by 9V battery. The amount of voltage the motor receives is controlled by the MOSFET, which is connected to the digital pin 6. The MOSFET, motor and current sensor are connected in series.

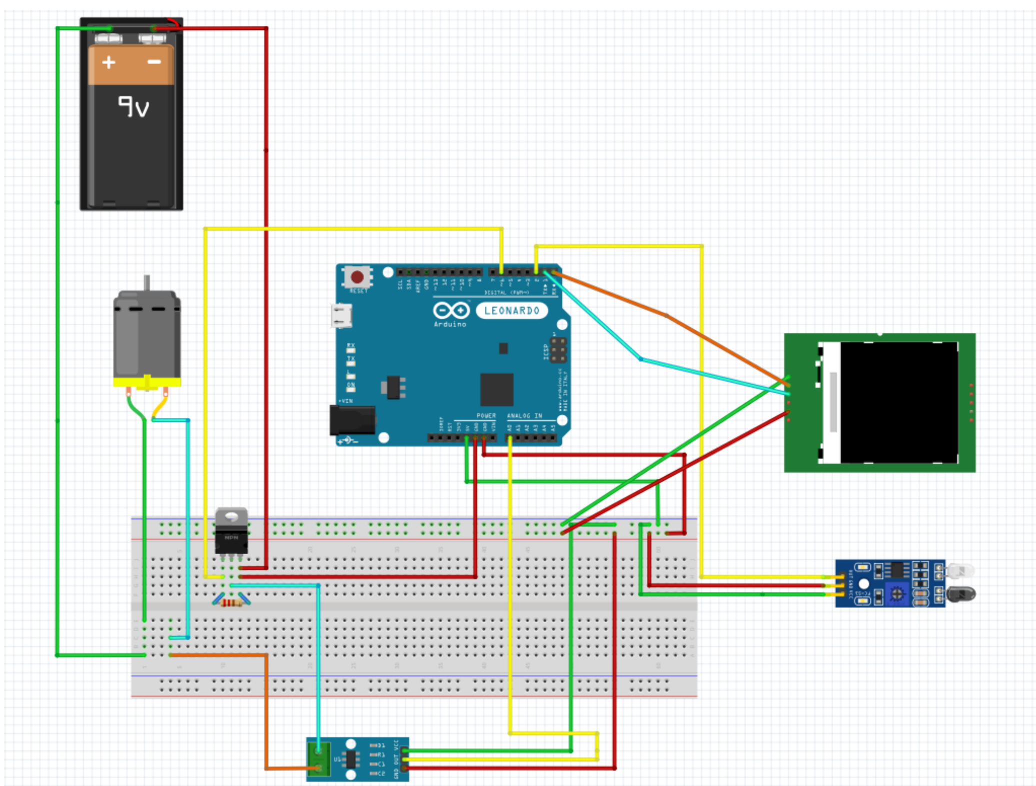


**Figure 4.** A schematic of the circuit diagram with all the components connected to the breadboard and Arduino.

# Gantt Chart

| | Tasks | Number of days | Percentage completion | Week 1<br>11-Jan | Week 2<br>18-Jan | Week 3<br>25-Jan | Week 4<br>1-Feb | Week 5<br>8-Feb | Week 6<br>15-Feb | Week 7<br>22-Feb | Week 8<br>1-Mar | Week 9<br>8-Mar | Week 10<br>15-Mar | Week 11<br>22-Mar | Week 12<br>29-Mar | Week 13<br>5-Apr | Week 14<br>12-Apr | Week 15<br>19-Apr | Week 16<br>26-Apr | Week 17<br>3-May | Week 18<br>10-May | Week 19<br>17-May | Week 20<br>24-May | Week 21<br>31-May | Week 22<br>7-Jun | Week 23<br>14-Jun |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Concept Ph | **Gantt Chart (26-Jan 3pm)** | | 100% | | | 26-Jan | | | | | | | | | | | | | | | | | | | | |
| | **First Sketch** | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | - Prelimenary Concept of outside and inside | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | - Design of mechanism | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | **Research** | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | a) Choosing the mechanism | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | - Theory and equations | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | - Voting on mechanism | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | b) Narrowing down the electronic/computing components | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | Narrowing down the equations | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | Choosing the motor | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | Research on graphs | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | Additional Components | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | c) Calculatin an hypothetical average cost | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | d) Understanding possible material families | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | e) C++ understanding for Arduino | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | **Indivdual Video Submission 1 (16-Feb 3pm)** | | 100% | | | | | | 16-Feb | | | | | | | | | | | | | | | | | |
| | **Presentation Concept Design (19-Feb 1.30pm)** | | 100% | | | | | | 19-Feb | | | | | | | | | | | | | | | | | |
| | a) Designing the presentation | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | b) Preparing for the final presentation | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | **Concept Design Report (16-Feb 3pm)** | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | a) Subgroup annexes | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | b) Sustainibility report | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | c) Financial report | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | d) Report assembly | | 100% | | | | | | 16.Feb | | | | | | | | | | | | | | | | | |
| Prototyping | **Model in CAD (each part of the machine)** | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | a) Construction and renders of individual compnents by each sub group | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | b) Assembly of components and renders | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | **Technical Drawing (25-Mar 3pm)** | | 100% | | | | | | | | | | | 25-Mar | | | | | | | | | | | | |
| | **Letter (25-Mar 3pm)** | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | a) Description of current design | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | b) Evaluation of design and next steps | | 100% | | | | | | | | | | | 25-Mar | | | | | | | | | | | | |
| | **Material Selection** | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | a) Material index/ constraints/ for each componemt | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | b) Final Shortlist of Materials (3 materials min.) | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | **Ordering** | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | **Prototype (19-Mar Whole Day)** | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | a) Preparing parts (out of cardboard for constructions) each subgroup | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | b) Construction of individual components | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | c) Integration of individual components into whole prototype | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | d) Additional further testing with liquids if possible | | 0% never done with prototype | | | | | | | | | | | | | | | | | | | | | | | |
| | **Testing** | | 0% | | | | | | | | | | | | | | | | | | | | | | | |
| | a) Selecting testing samples | | 0% | | | | | | | | | | | | | | | | | | | | | | | |
| | b) Structural practicality and improvements | | 0% | | | | | | | | | | | | | | | | | | | | | | | |
| | c) Actual sample testings | | 0% | | | | | | | | | | | | | | | | | | | | | | | |
| | **Software** | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | a) Writing the pseudocode and determining different functions | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | b) Implementing the code and making modifications | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| Final Design | **Peer Marking (10-Jun 3pm)** | | 0% | | | | | | | | | | | | | | | | | | | | | | 10-Jun | |
| | **Group Design Defence (11-Jun Whole Day)** | | 0% | | | | | | | | | | | | | | | | | | | | | | 11.Jun | |
| | a) Familiarising our design and progress | | 0% | | | | | | | | | | | | | | | | | | | | | | | |
| | b) Distributing responsibility within each subgroup | | 0% | | | | | | | | | | | | | | | | | | | | | | | |
| | **Reprint new parts** | | 66% | | | | | | | | | | | | | | | | | | | | | | | |
| | a) Identification and Manufacture of new parts needed | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | b) Construction of individual components into new prototype | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | c) Testing of final versions | | 0% | | | | | | | | | | | | | | | | | | | | | | | |
| | **Adjustments on technical Drawing** | | 50% | | | | | | | | | | | | | | | | | | | | | | 11-Jun | |
| | **Indivdual Video Submission 2 (6-Jun 3pm)** | | 0% | | | | | | | | | | | | | | | | | | | | | | | |
| | **Final report (3-Jun 3pm)** | | 100% | | | | | | | | | | | | | | | | | | | | | 3.Jun | | |
| | a) Subgroup annexes | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | Description of components and how to construct them | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | Wiring and coding instructions explained | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | b) Sustainibility report | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | Justifying material and processing choice | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | Evaluating overall environmental impact | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | c) Financial report | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | Breakdown of expenditure per subgroup | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | Justifying overall expenses | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | d) Final report assembly | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | Finalising the introduction | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | Combining the different subheadings together | | 100% | | | | | | | | | | | | | | | | | | | | | | | |
| | **Final Presentation and Test Day (14-Jun Whole Day)** | | 0% | | | | | | | | | | | | | | | | | | | | | | | |
| | a) Make slideshow and script | | 0% | | | | | | | | | | | | | | | | | | | | | | | 14-Jun |
| | b) Run throughs an practice | | 0% | | | | | | | | | | | | | | | | | | | | | | | |

The red dates in green are the dates we finished the respective tasks. The three-weeks long yellow columns are the weeks that we, as the company, took some time off for Easter and for exam preparation.

## Company Wide Control Tool for the Plant

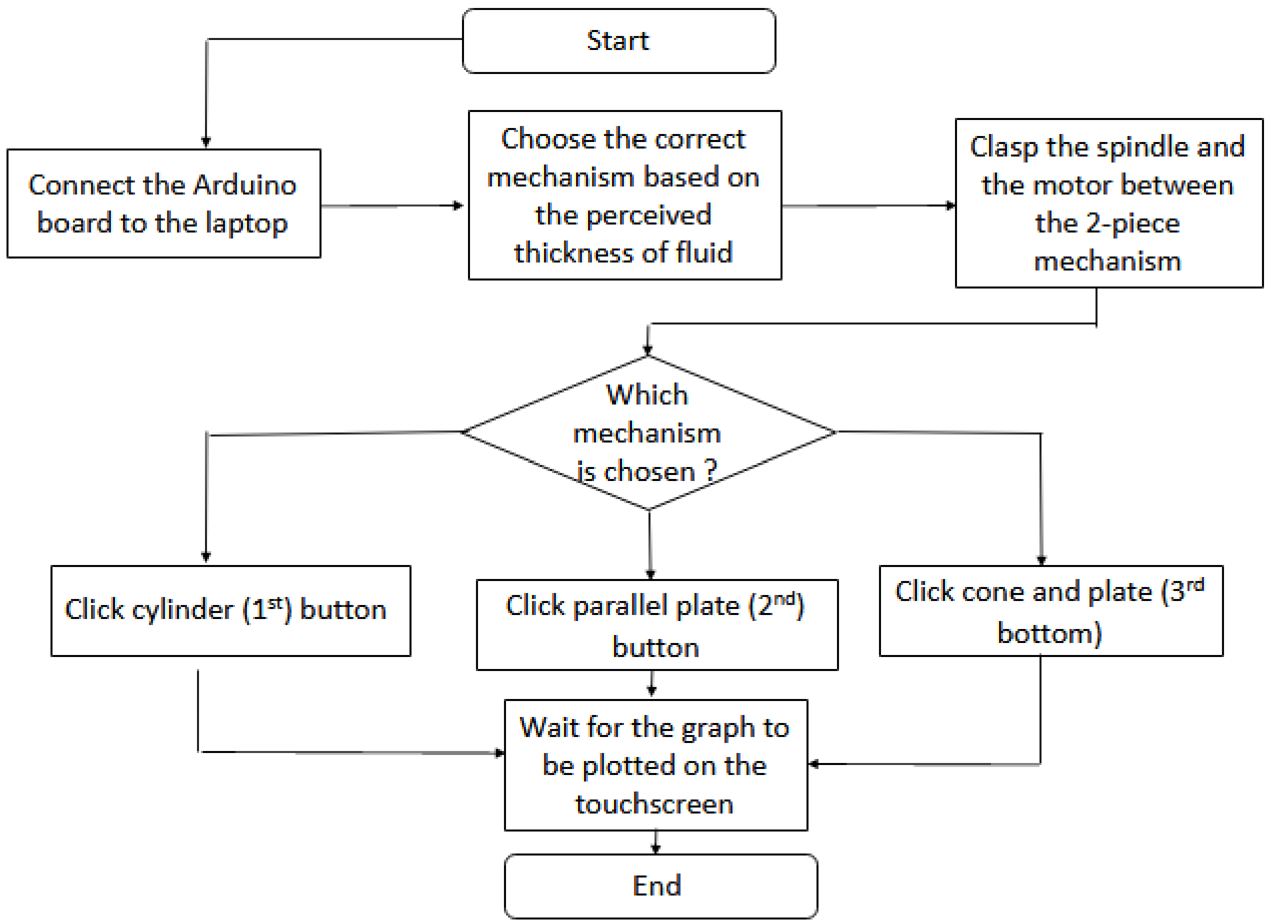


**Figure 5.** A flow chart describing the sequential order of operating the viscometer.

## Sustainability Report

Many aspects relating to sustainability were considered while choosing the final materials for the viscometer. The outer case of the viscometer was made from PMMA which is 100% recyclable. For the inner parts of the viscometer, the department provided a PLA spool free of cost. Initially the material which was going to be used was PETG. However, the PETG spool would have to be specially ordered and shipped. This would add an additional carbon footprint due to the added manufacturing and transportation processes, and would not provide for the most sustainable use of the resources at our disposal. The PLA spool was utilized judiciously in such a way that only 1 spool was needed. The PLA parts will be labelled with a unique Resin Identification Code which is helpful in PLA recycling.

Painting the viscometer with spray paint was initially under consideration. However, this would deem the PMMA unrecyclable and hence the idea was scrapped.

Initially the PMMA sheets that were laser cut had a few design flaws with respect to the sizes and locations of the laser cuts. Since the cutting had to be redone on new PMMA sheets it was also decided that the size of the box would be made more compact in order to enable material savings as well as cost reduction. This would be immensely beneficial for large scale manufacturing where a production of even a 100 viscometers would lead to a materials savings worth 0.7 tonnes of PMMA. The flawed sheets were also recycled efficiently to prototype the hinge mechanisms so that when they were deployed on the final sheets the mechanism would work accurately.

The design for the 3D prints was also improved after the initial 3D prints such that the mechanisms would now have dimensions which allowed the prints to be hollow from within while maintaining their shape. This leads to PLA filament savings by about 40% and a spool can now be utilized for longer.

The company is starting a green initiative under which we will accept back all viscometers which have been manufactured more than 5 years ago for recycling purposes. The customers can contact us and drop off their old viscometer at a specific drop off locations and will be rewarded with additional spindles which can be purchased with their next viscometer. The old viscometer will be disassembled according to the different materials used. The PMMA sheets will be reprocessed at a recycling facility that we have tied up with and will be used to make new viscometers. The electronic components will be segregated and sent to an electronics recycling plant. The unique RICs on the PLA parts will be used to organize and recycle PLA at the recycling plant we have tied up with. The PLA parts will be inspected for degradation and if their condition is usable they will be reprocessed and mixed with new PLA to make 3D printing filaments in a careful way such that the structural strength of the switching mechanism is not compromised. If their condition is degraded and they are not usable the PLA will be composted (which takes up to 3 months[4]) since PLA is biodegradable.

| Material | Carbon footprint (kg/kg) | Water usage (l/kg) | Energy usage (MJ/kg) | Toxicity | Recyclability |
|---|---|---|---|---|---|
| PMMA[5] | 8.73 | 76.1 | 153 | Non-toxic | Recyclable |
| PLA[6] | 5.40 | 20.8 | 77.0 | Non-toxic | Recyclable |

## Financial Report

Throughout the entire process of designing and creating the Imnometer, the relative cost of production was taken into account considerably, trying to decrease the expenditures as much as possible while still maintaining a high standard in quality. The company firmly believes that a lower cost of production of the machinery would result in a greater demand for a possible mass production of the product. Therefore, the total expenditures needed to be lower than the initial budget set at £150 for the production of the first unit. The two main expenditures were the touchscreen and the structural materials used.

In order to have a functional user-friendly device, the company decided to include a touchscreen interface in the final design of the project. Although its cost, £29.98, is significantly high compared to the vast majority of the expenditure, this touchscreen does improve the quality of the product drastically and provides a better user experience, therefore adding value to the product. The second significant expense is the structural materials used, mainly the clear cast Perspex acrylic which was laser cutted and used for the outer layer of the box. The total amounts spent on the acrylic sheets was £35.53. This number is significantly lower than the value predicted on the concept design report, because it was possible to reduce the expenditure by choosing thinner sheets that would still maintain structural integrity. This choice highly benefitted Imnovation's budget and will be key to profiting from the machine when mass produced.

Table 1 below shows all expenditures of Imnovation on the left and the relative costs of production per unit of the product on the right.

**Table 1.** List of Expenditure.

| **Materials** | **Total Price** | **Price per Unit** |
|---|---|---|
| 5.0mm clear cast Perspex® acrylic, 1 400x300mm sheets [7] | £4.55 | £4.55 |
| 5.0mm clear cast Perspex® acrylic, 10 300x200mm sheets [7] | £2.53£ each for a total of £25.30 | £2.53 each, for 6 pieces: £15.18 |
| 5.0mm clear cast Perspex® acrylic, 1 500x300mm sheets [7] | £5.68 | £5.68 |
| IR sensor [8] | £5.99 | £5.99 |
| Volt meter sensor for Arduino [9] | £3.99 | £4.55 |
| Door hinges [10] | £4.69 | £8.99 |
| Nextion 3.2" Display Screen HMI Smart 3.2 inch LCD Module 400x240 [11] | £29.98 | £29.98 |
| 3D printing spool | £20 | £20 |
| Total | £100.18 | £75.84 |
| Under budget | £49.82 | £74.16 |

To build the product, several instruments have been asked to the department. Table 2 is a list of the ones borrowed and used. The company will invest in them if the project becomes mass produced.

**Table 2.** List of instruments asked to the department.

| | |
|---|---|
| 10x100 mm file | Saw |
| 30x200 mm file | Laser cutter |
| Drill | 3D printer |
| 9V battery holder | |

Overall, the company succeeded to construct the Imnometer by remaining significantly underbudget, while being able to maintain the high standards of quality set for the product.

## Assessment of Project Status

Imnovation has been working hard in the past months to make the Imnometer work. The most important feature of our viscometer is the three different mechanisms to measure the viscosity of various Newtonian liquids. Low viscosity fluids like water are best measured using the bob-and-cup mechanism since this geometry has a larger surface area to produce a larger response to a given shear rate. This mechanism is also good for volatile liquids, although more liquid will have to be used compared to the other two. The parallel plate mechanism can be used for more viscous fluids, such as honey, as it applies less shear to the fluid and avoids any axial stresses in the sample that are present before the measurements. Furthermore, wall-slip or wall depletion can be avoided. The last mechanism is the cone-and-plate mechanism. This is the most suitable mechanism for non-Newtonian fluids. It ensures homogeneous flow and uses low volumes of the liquid. Furthermore, it is convenient to clean.

Apart from the actual design and production of the three mechanisms using 3D printing, a convenient switching mechanism had to be designed. This mechanism had to securely hold the spindle in place and also make it easy to replace one spindle with the next. Our final design includes a two-piece clip mechanism, that connects the spindle to the motor. To remove the spindle easily, the part, where the circuit is located with the motor can be lifted, so that the spindles can be removed and easily inserted back into the viscometer. The different mechanisms are designed to be light and easy to transport. Further the whole design of the viscometer has been optimized to be easily transportable by the user. The code has been also adjusted for all three mechanisms; to give the correct measurements and display the graphs on the LCD touch screen as well as to give the user an overview of the viscosity over time. The data received from the viscometer will be analysed using linear regression and then displayed. This is possible from the data gather from both Newtonian and non-Newtonian fluids.

The user interface is designed to be easily understood by the user. The desired mechanism is selected via the touchscreen. This button press will also start the measurement. A progress bar informs the user about the time that the measurements take, while a graph will also be displayed showing the value of the viscosity over time. Lastly, the final value for the viscosity will be displayed.

Further, the final product was produced using the desired budget. It was made cost efficient by using easily accessible materials for the casing, the spindles for the three mechanisms, and the circuitry.

Sustainability was achieved by careful consideration of the materials chosen, such as PMMA, which is 100% recyclable. Further, we tried reducing waste during the production process. Sustainability has also been considered in the design process, by reducing the size of the viscometer. Lastly, our green initiative will ensure ultimate sustainability.

Several problems were faced during the design and production of the viscometer. Our goal to not having to use a laptop for the measurements was not accomplished, since the LCD screen had to be powered through the laptop. Further, problems were faced with the communication between the screen and the Arduino, which made it impossible for us to plot the shear strain over the shear rate and display that graph on the LCD screen. The graphs that are displayed for the user with our current design can also not be downloaded and the data gather from the viscosity measurements must be noted down by hand. The problems faced during the production was that the design had to be re-done two times to fit the three mechanisms and that the size of the design had to be reduced to accomplish the goal of being easy to transport. Further, the 3D prints of the 3 mechanisms turned out to be not as smooth as expected, making getting accurate measurements more difficult. Using a different manufacturing technique for the mechanisms would likely resolve this problem. Lastly, there is no way to download the data at the moment.

Despite these problems Imnovation's engineers have faced, the final version of the Imnometer turned out to be a functioning, easy to use, cost efficient and sustainable viscometer ready to leave a mark.

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