Reducing Drag Forces on Submerged Bodies by Varying Surface Finish

Mech 305 Lab Section 2 Team 7

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Abstract

The purpose of this experiment was to study the drag characteristics of a submerged body based on varying surface roughness. The inspiration behind this comes from the fact that a few of our team members are avid canoeists and we would like to know whether there is an easier way for us to canoe. We hope to learn more about various surface finishes and roughness and their impact on the drag coefficients of streamlined objects. We experimented using 3D-printed streamlined bodies covered with various coatings. We added a metal rod as a weight inside each shape to ensure the body does not float and falls in a swimming pool and attached a wooden rod at the tail of each object to ensure the object does not twist and turn as it falls. We expect smoother materials to perform better because they experience less skin friction, and before conducting the experiment, we were curious to see where hydrophobic material and butter would fit in. Based on the results, generally smoother surfaces performed better, with butter and the hydrophobic coating performing best, in terms of drag.

Introduction

Finding ways to reduce drag is always of important engineering interest, which makes this project interesting. To answer the question of how surface roughness affects drag characteristics, we considered a range of surface finishes comprised of food-grade plastic wrap, butter coating, standard 3D-printed finish (which tends to be rough), hydrophobic coating, sanded smooth finish, spray-painted and aluminum foil. We believe these materials serve their function of providing a wide range of surfaces because it includes smooth and rough surfaces, surfaces coating that can be created using household items and a few interesting ones like butter and the hydrophobic spray. The ideal surface will face the least amount of drag and therefore, if a canoe was covered with that material, the canoeist would exert the least amount of energy to move through the water.

After doing some preliminary research, we came across a few studies that we can compare our results to. P.-As. Krogstad and R. A. Antonia varied the surface roughness of an object and discovered that surface roughness significantly affects the turbulent characteristics and therefore increases drag. Concerning hydrophobic surfaces, Ling, Hangjian et al. discovered that higher surface roughness reduces the skin friction effects. Based on this research we expected smoother surface finishes such as the sanded model and the one covered with plastic wrap to experience lower drag compared to the models which had a rougher exterior such as the raw 3D-printed finish and the one covered with aluminum foil. We expect this because objects that are smoother tend to have lower factors of skin friction. We were not certain how the hydrophobic surface or its cheaper counterpart the butter coated surface would affect the fluid drag and were quite surprised to see their performance. (Ling, 2016)

Methods

The methodology of this experiment is split up into two sections: the setup and the test procedure. The setup shows the physical experiment apparatus, as well as the methods of data collection. The test procedure shows how the trials were done and the calibration that took place.

At the center of this experiment are the 3D-printed streamlined bodies with various surface finishes. The wetted area of a canoe can be simplified as a streamlined body, instead of performing our experiments using a full canoe, we simplified the experiment by using streamlined bodies with a WORTMANN FX 63-137 airfoil shape which was chosen because this airfoil produces little form drag at low velocities. The reason we wanted to use 3D printed pieces instead of a canoe is because we no longer had to consider wave drag and to greatly simplify the apparatus of the experiment.

Setup

Consider Figure 1 below, showing each wrapped or coated body standing on a cylindrical stand that was used during 3D-printing. Figure 2 shows the close-up of the body that consists of a red part, blue part, metal rod inside the body and a wooden rod glued at the tail. The mass of each body as shown in Figure 2 was measured using an electronic balance.

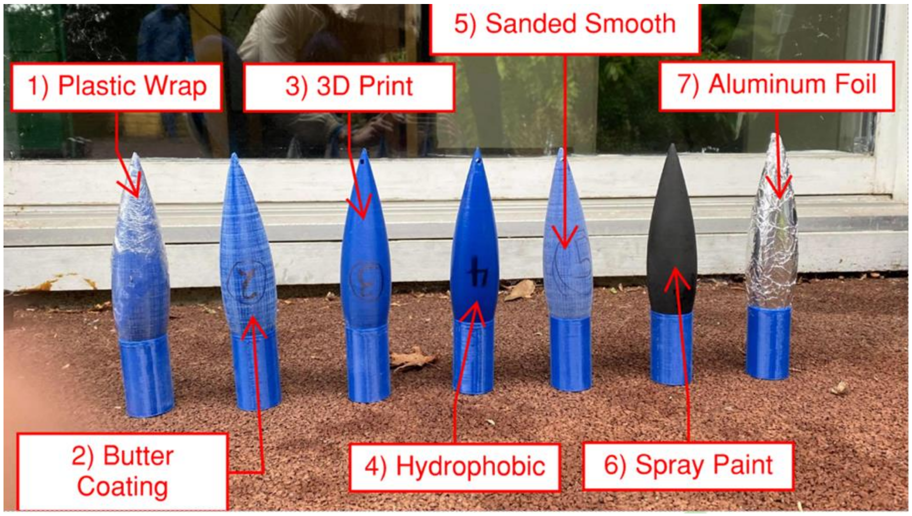


Figure 1: The Streamlined Bodies with Various Surface Finishes

Figure 2: Close-up of the 3D-printed body

As previously mentioned, these materials provide a strong range of surface finishes and roughness. The physical apparatus was built using a wooden 2x4 with a spool of fishing wire in the middle. These bodies were attached to the fishing wire and would unspool as the body falls through the water. In the center of the spool, we attached a rotary encoder and wired it to an Arduino, which gave a rotary position that could be converted to time. Consider the setup shown below in Figure 3 and Figure 4:

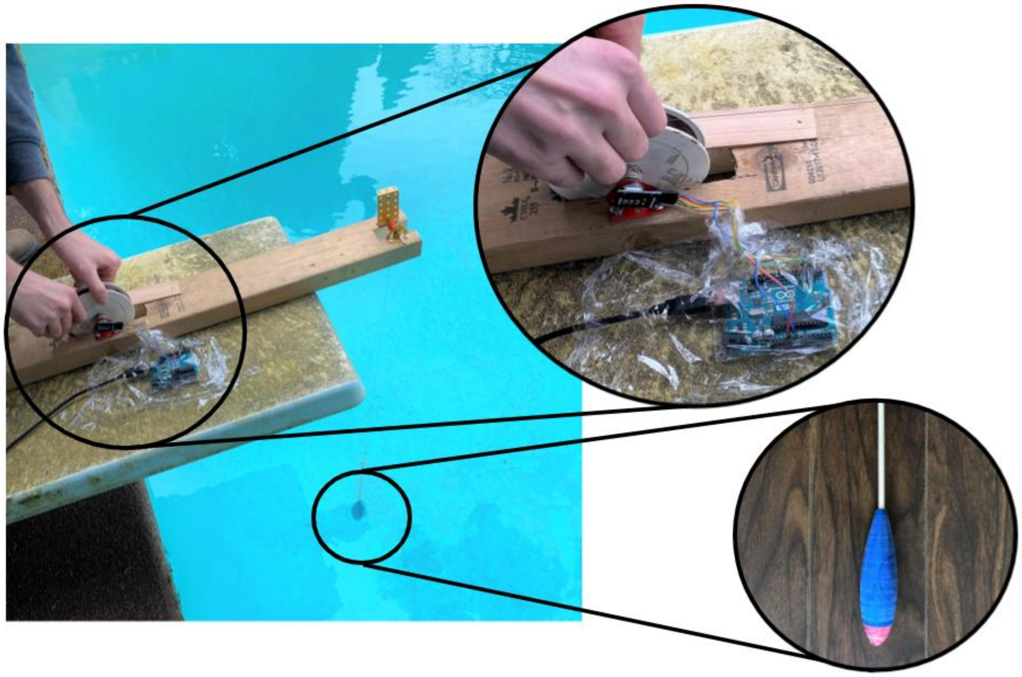


Figure 3: Experimental Apparatus Setup

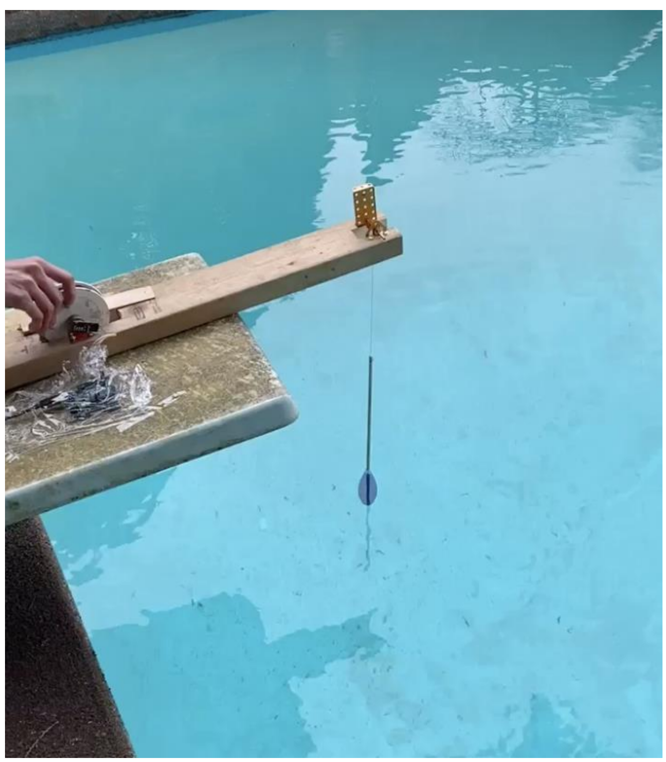


Figure 4: Experimental Apparatus Setup

The streamlined body is attached to the fishing wire that goes over a smooth pulley to minimize frictional losses. As seen above in Figure 3 in the bottom circle, each streamlined body was glued on a wooden rod at its tail. This wooden tail prevented the body from twisting and turning as it went through the water, and its motion was kept entirely vertical. The rotary encoder, which was wired to Arduino, came with its printed circuit board (PCB). The schematic of the circuit is shown in Figure 5 and Figure 6 below.

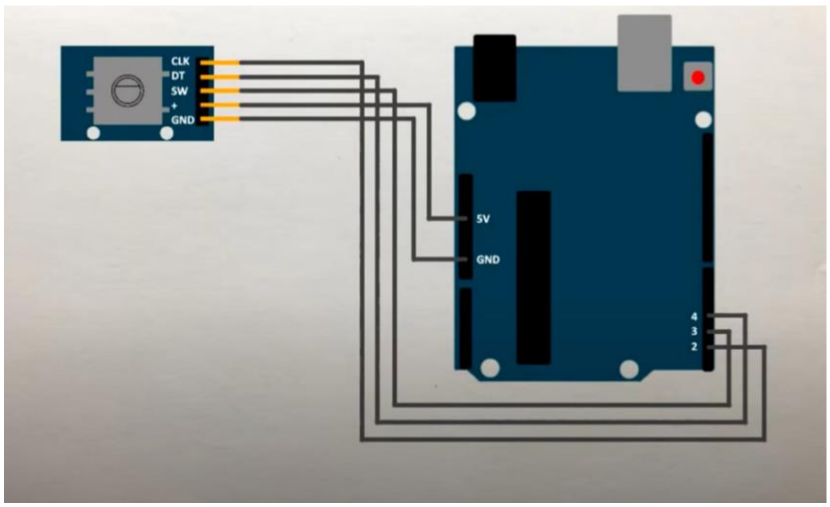


Figure 5: Circuit Schematic of the Rotary Encoder PCB and Arduino (Account, 2019)

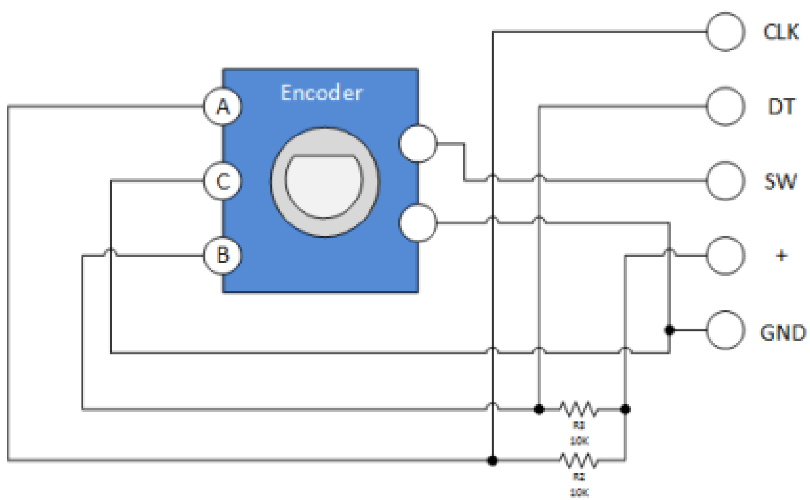


Figure 6: Circuit Schematic of Rotary Encoder PCB and Arduino (Arduino Forum, 2018)

Figure 5 shows how the encoder's PCB is wired to the Arduino board and Figure 6 shows the schematic of the PCB itself. We were able to use the PCB, so we did not need to assemble the circuit shown in Figure 6. Once the encoder is set up and fits well in the center of the fishing wire's spool, the apparatus is ready. To read the encoder value, we used the Arduino script shown in Appendix A. The output of this was the rotary position of the encoder and a timestamp, which could then be processed to find the displacement, velocity, and acceleration of the object as a function of time.

Test Procedure

The modifications we made to the streamlined surfaces, modifying the surface finishes while adding a wooden rod at the tail to stabilize it in water, resulted in a slight variation in the weight. We tabulated the results to ensure that we did not introduce any unnecessary errors in our calculations by measuring the masses and considering them in our calculations.

The friction in our pulley system would result in a systemic error that we wanted to minimize. The static friction of the pulley was easily found by increasing a known mass suspended from the pulley until the mass started moving. The dynamic friction was the one we were more interested in since that would be the type of friction in effect when our streamlined body would be moving through the water, but it was harder to measure accurately. To measure the dynamic friction in the system we suspended a known mass from the pulley and gave it a light push to ensure that it started moving, we decreased the weight till we found the body would stop moving on its own, the maximum weight that could be suspended from the pulley in motion and have it stop on its own was the dynamic friction force. We repeated the static friction test five times and the dynamic friction test fifteen times to minimize the random error in our calibration constants. We intended to use the dynamic friction force for our force calculations while using the static friction force to set the maximum possible friction in the system. Our static and dynamic friction forces are listed in Table 1 below.

Table 1: Static and Dynamic Friction Forces

Type of Friction	**Value of the Friction Force**
Static Friction	0.79 N
Dynamic Friction	0.40 N

We attached our streamlined bodies to the setup outlined above and allowed them to free-fall in the swimming pool. We had tied a knot in the spool to ensure that our streamlined body would only fall a fixed length and most importantly, avoid hitting the bottom of the pool as this would break the body. The streamlined body with the thread attached to it rotated the encoder as it fell in the water and the data was recorded by the Arduino. Each trial of the streamlined body falling through water lasted less than two seconds because the pool was only 8.3 feet (2.5m) deep and the body travelled for only 7 feet (2.13m). Due to the short duration of each experimental run, we were not able to preprocess the data in any way without causing a bottleneck at the encoder. Thus, we recorded the change in ticks in the encoder and used the system timestamp to understand how the encoder ticks changed with time. We performed a total of ten trials with each surface finish to minimize random error in our measurements.

Results

Table 2: Mass of the body for each surface finish

Surface Finish	**Mass [kg]**
Smooth	0.2728
Plastic	0.2731
Butter	0.268
3D-Print	0.2665
Hydrophobic	0.2656
Spray-Painted	0.2685
Aluminum	0.2669

Below are plots showing the displacement over time of each of the objects with different surface finishes. In Figure 7, some trials end with a flat line, this data represents the time when the streamlines body was left at the bottom of the pool for an extended period. These long periods when the body was not moving were removed before the trials were analyzed.

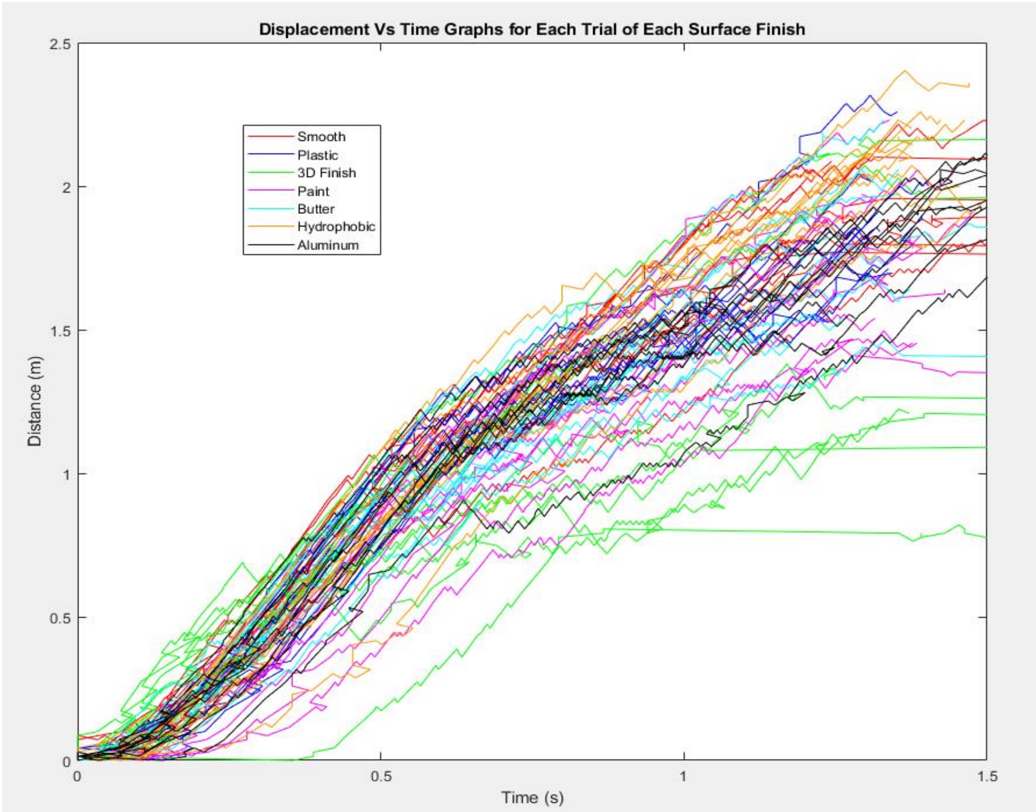


Figure 7: Displacement vs Time Plot – All Trial, All Surface Types

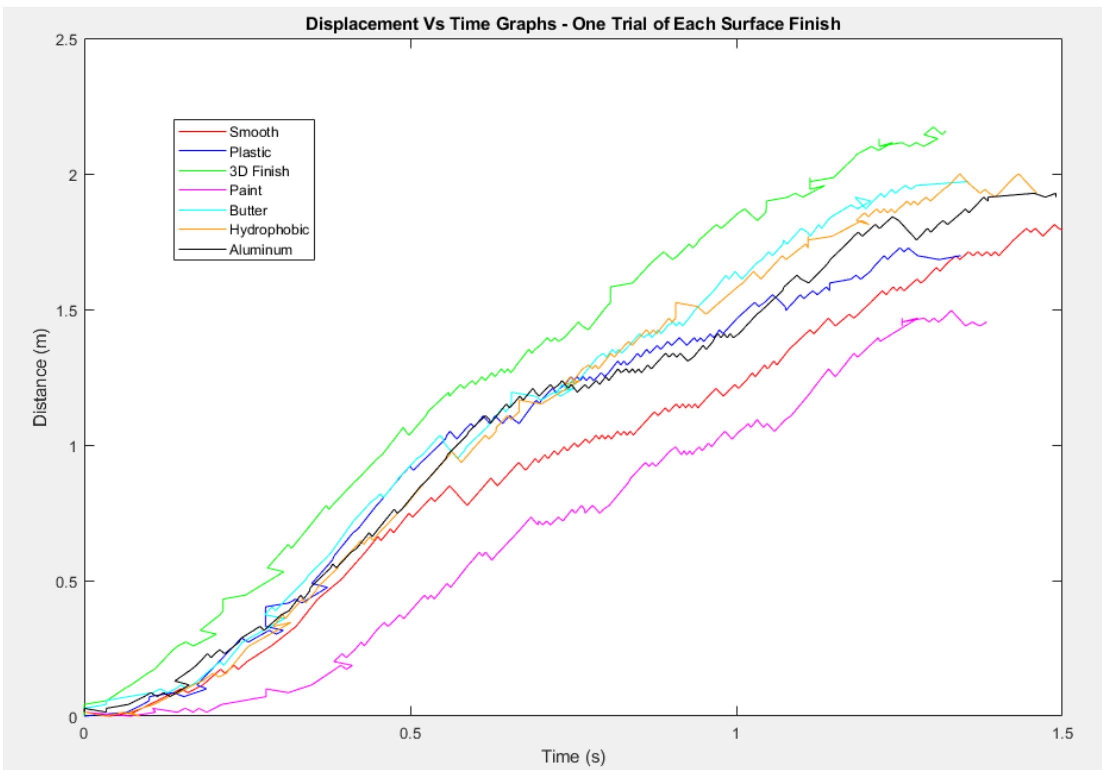


Figure 8: One Trial of each Surface Finish to Show the Displacement Curve More Cleary

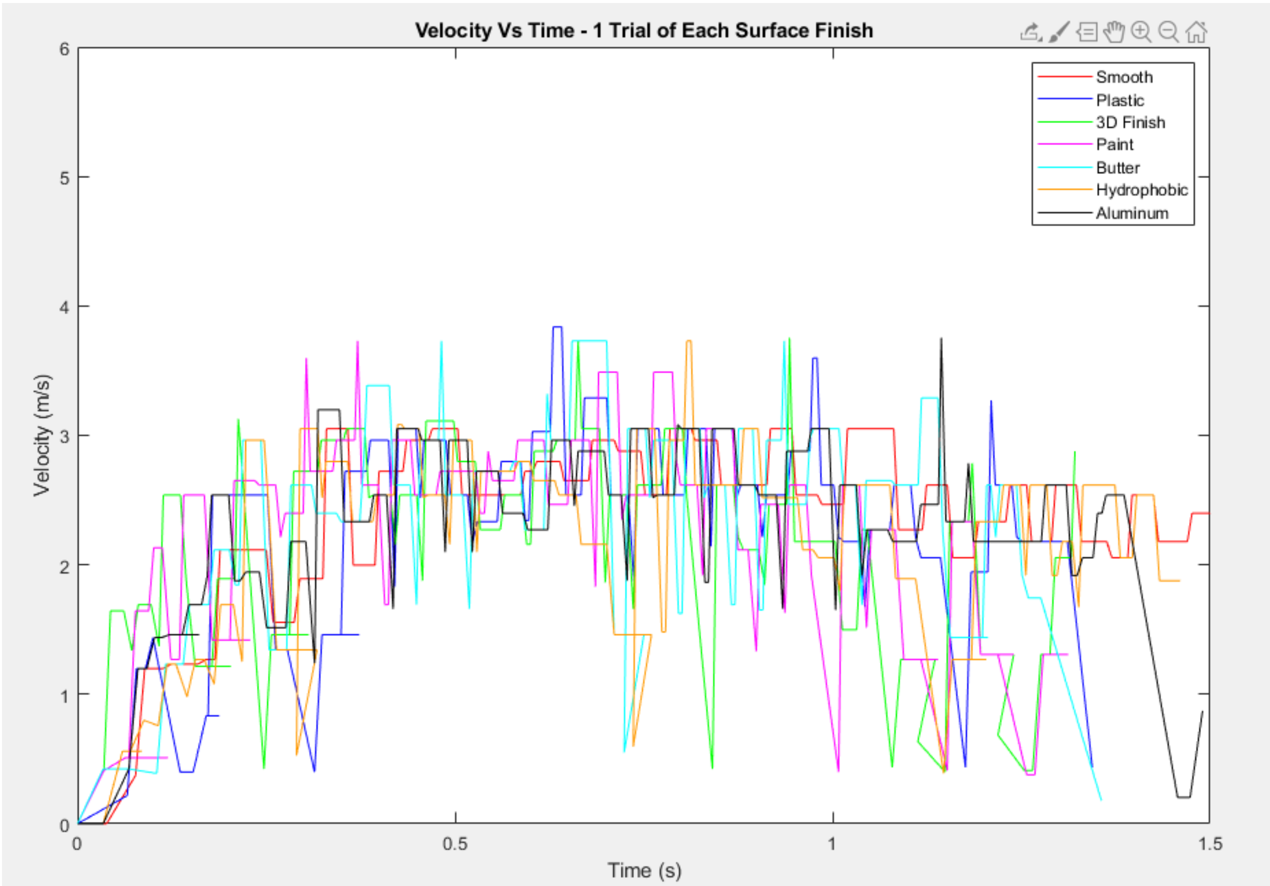


Figure 9: One Trial of Each Surface Finish to Show to Trend of the Velocity Curve

Analysis & Discussion

Encoder Data Analysis

Table 3: Sample of Raw Encoder Data – Smooth Object

Trial 1	Trial 2	Trial 3
12:03:21.527 -> 1	12:04:00.562 -> 1	13:29:53.430 -> -1
12:03:21.527 -> 0	12:04:00.562 -> 0	13:29:53.464 -> -2
12:03:21.604 -> -1	12:04:00.595 -> -1	13:29:53.464 -> -3
12:03:21.604 -> -2	12:04:00.631 -> -2	13:29:53.464 -> -2
12:03:21.604 -> -3	12:04:00.631 -> -3	13:29:53.464 -> -3
12:03:21.640 -> -4	12:04:00.631 -> -4	13:29:53.499 -> -2
12:03:21.640 -> -5	12:04:00.668 -> -5	13:29:53.499 -> -3
12:03:21.640 -> -6	12:04:00.668 -> -6	13:29:53.499 -> -2
12:03:21.675 -> -7	12:04:00.668 -> -7	13:29:53.499 -> -1
12:03:21.675 -> -6	12:04:00.668 -> -6	13:29:53.499 -> 0
12:03:21.675 -> -7	12:04:00.668 -> -7	13:29:53.499 -> -1
12:03:21.709 -> -8	12:04:00.702 -> -8	13:29:53.536 -> -2
12:03:21.709 -> -9	12:04:00.702 -> -9	13:29:53.536 -> -3
12:03:21.709 -> -10	12:04:00.702 -> -10	13:29:53.536 -> -4
12:03:21.709 -> -11	12:04:00.702 -> -11	13:29:53.536 -> -5
12:03:21.709 -> -12	12:04:00.702 -> -12	13:29:53.536 -> -6
12:03:21.743 -> -11	12:04:00.739 -> -13	13:29:53.536 -> -7
12:03:21.743 -> -12	12:04:00.739 -> -14	13:29:53.536 -> -8
12:03:21.743 -> -13	12:04:00.739 -> -13	13:29:53.571 -> -9
12:03:21.743 -> -12	12:04:00.739 -> -14	13:29:53.571 -> -10

*Note: The green & yellow cells indicate repeating time stamps for these three trials

Using the encoder data, we expected to get a unique time step for every "tick" throughout the revolution of the encoder. When physically turning the encoder by hand we noted there were 20 noticeable detents ("tick") for one revolution of the encoder. This indicated to us that we would expect 20 ticks, and therefore 20-time stamps for every revolution of the spool.

In contradiction to our physical inspection, when the encoder was rotated quickly, the number of ticks per revolution would vary, sometimes reaching 70 electronic steps.

Using a measured radius of the spool of thread to be 45.8mm we can calculate the distance our object travels per revolution:

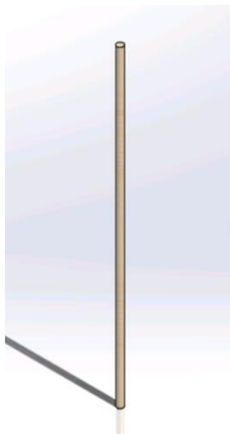
$$circumference = 2 * p * r = 2 * p * 0.0458m = 0.28777m$$

This means for every full revolution of the spool & encoder our object travels 0.288m through the pool. Based on our encoder giving 20 timestamps for every revolution, we should expect the object to move 0.0144m or 1.44cm for every tick of data received. The online datasheet can be referred to in Appendix D.

Buoyancy

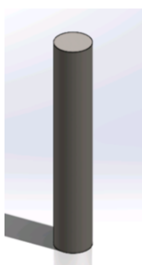
Due to the nature of our experiment, we needed to address the effect of buoyancy on our object, as it was being measured as it dropped through the water.

Figure 12-14 below show the different part that forms the whole body which consists of a pinewood stick, a carbon steel rod and 3D-printed test object.



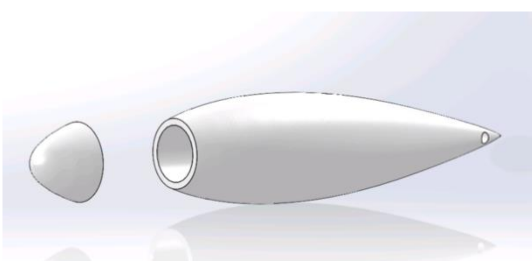
Pine Wood used to stabilize object
¼” Diameter x 12” Long
Estimated Density: 0.42 kg/m^3
Volume: 9.65x10^{-6} m^3
Mass: 4.05x10^{-6} kg

Figure 10: 1/8" Diameter Wood Stabilizer



Carbon Steel used for weight inside the object
0.02m Diameter x 0.12m Length

Figure 11: Steel Weight Insert



Test Object
Volume: 1.049x10^{-4} m^3
Total Mass (includes stick, steel weight and surface substance): 0.2728 kg (Smooth object)

Figure 12: 3D Printed Test Object

Calculation used to determine buoyancy of Smooth Test object (Mott & Untener, 2015):

Assumptions:

- Density of water at 15 Celsius is 999.1 kg/m^3
- Downwards force considered positive
- Density of pine wood is 0.42 kg/m^3

$$Fb_{stick} = Buoyancy\ force\ of\ stick = Volume\ of\ stick * Density\ of\ water * Gravity$$

$$Fb_{object} = Buoyancy\ force\ of\ object = Volume\ of\ object * Density\ of\ water * Gravity$$

$$F_g = Gravitational\ force\ of\ stick\ and\ object = Mass\ of\ stick\ and\ object * Gravity$$

$$F_{drag} = \frac{1}{2} * Density\ of\ stick\ and\ object * Velocity^2 * Area * Drag\ Coefficient$$

$$\begin{aligned} F_{net} &= Net\ force\ experienced\ by\ object\ and\ stick \\ &= F_g - Fb_{stick} - Fb_{object} - F_{drag} \\ &= Mass\ of\ object\ and\ stick * Acceleration \end{aligned}$$

This equation is used in the next sections to plot the Drag Coefficient against Reynolds number Graph for each surface finish.

These equations can also be used to calculate the theoretical maximum acceleration for each surface when it travels through water. This is a crucial step as it will allow us to determine if the velocity and acceleration graph from the encoder data matches the law of physics.

Using the smooth surface finish as an example, the maximum theoretical acceleration can be calculated by removing Drag Force, F_d from the F_{net} equation and equating it to the mass of stick and object multiplied by acceleration.

$$F'_{net} = Net\ force\ experienced\ by\ object\ and\ stick$$
$$= F_g - Fb_{stick} - Fb_{object}$$
$$= Mass\ of\ stick\ and\ object * Maximum\ theoretical\ acceleration$$

$$F_g = (0.2728\ kg)\left(9.81\ \frac{m}{s^2}\right) = 2.676\ N$$

$$Fb_{stick} = -(9.65 * 10^{-6}\ m^3)\left(999.1\ \frac{kg}{m^3}\right)\left(9.81\ \frac{m}{s^2}\right) = -0.0946\ N$$

$$Fb_{object} = -(1.049 * 10^{-4}\ m^3)\left(999.1\ \frac{kg}{m^3}\right)\left(9.81\ \frac{m}{s^2}\right) = -1.0283\ N$$

$$F'_{net} = 2.676\ N - 0.0946\ N - 1.0283\ N = 1.553\ N$$

$$Maximum\ theoretical\ acceleration = \frac{1.553\ N}{0.2728\ kg} = 5.693\frac{m}{s^2}$$

Since the maximum theoretical acceleration is 5.693 for smooth surface finish, the maximum acceleration of the body from the encoder data should not exceed this value since drag will reduce the maximum acceleration, intuitively and as seen from the equation.

Table 4: Theoretical Maximum Acceleration for each Surface Finish

Surface Finish	**Theoretical Maximum Acceleration [m/s^2]**
Smooth	6.040
Plastic	6.045
Butter	5.973
3D-Print	5.951
Hydrophobic	5.939
Spray-Painted	5.980
Aluminum	5.957

Calculating Velocity & Acceleration

Using the displacement data calculated using the method in the previous section, we are able to calculate the velocity and acceleration of the streamlined bodies. Velocity is given by the equation V= $Displacement/Time$, using the displacement we can approximate the instantaneous velocity of a point n as:

$$V_n = \frac{d_{n+1} - d_n}{t_{n+1} - t_n}$$

Where d is displacement and t is time. Our first issue was that the timestamps given by the computer were not unique, often repeating the same timestamp several times as can be seen in Table 3. The way we solved this issue was by linearly interpolating between data points. In Table 5 below, it can be seen how the times were divided into equal increments to achieve a continuous velocity.

Table 5: Convert time into Continuous Range

Smooth	Trial 1
Time (s)	Tick
0	1
0	0
0.077	1
0.077	2
0.077	3
0.113	4
0.113	5
0.113	6
0.148	7
0.148	6
0.148	7
0.182	8

→

Smooth	Trial 1
Time (s)	Tick
0	1
0.0385	0
0.077	1
0.089	2
0.101	3
0.113	4
0.125	5
0.136	6
0.148	7
0.159	6
0.171	7
0.182	8

With unique time and displacement values we were able to calculate the velocities of each trial (seen in figure 9). We want velocity because it will allow us to calculate the coefficient of drag and the Reynolds number at each timestep.

The next step was calculating the acceleration of each trial. An issue we immediately ran into was that the data from the encoder did not have the necessary resolution to calculate instantaneous acceleration. The best way we found to calculate acceleration was to find a best fit curve to the velocity data we just calculated, and then take the derivative of this equation to find acceleration.

To find the best fit of our velocity data we assumed the velocity function would take the form of:

$$V = A * \left(1 - exp(-B * t)\right)$$

As shown by the trend of the plot in Figure 9, where A is the terminal velocity and B is a positive time constant. We followed a derivation performed by the University of Texas (Fitzpatrick, 2011) to arrive at the above velocity function. We could not find a built-in function to find the best fit curve for this type of function, so we chose to implement a least-squares regression. Below is a summary of the least squares' equations:

$$Error = \sum \left(V - V_{pred}\right)^2 = \sum \left(V - A\left(1 - exp(-B * t)\right)\right)^2$$

To minimize the error function:

$$\frac{\partial Q}{\partial A} = \frac{\partial Q}{\partial B} = 0$$

We derived this system of equations:

$$\sum V\left(1 - exp(-B * t)\right) = A \sum (exp(-B * t) - 1)^2$$

$$\sum V\left(A * B * exp(-B * t)\right) = A^2 * B \sum exp(-B * t) - exp(-B * t)^2$$

Using the excel solver package we were able to find the A and B coefficients by solving the system of equations above. Below are the velocity data and best fit curve for the hydrophobic surface finish. In figure 14, all of the best fit curves have been compiled, it can be seen that the paint surface finish has the highest terminal velocity, note that this is not indicative of the drag coefficient as other surface finishes were less dense, and therefore their terminal velocities would be lower.

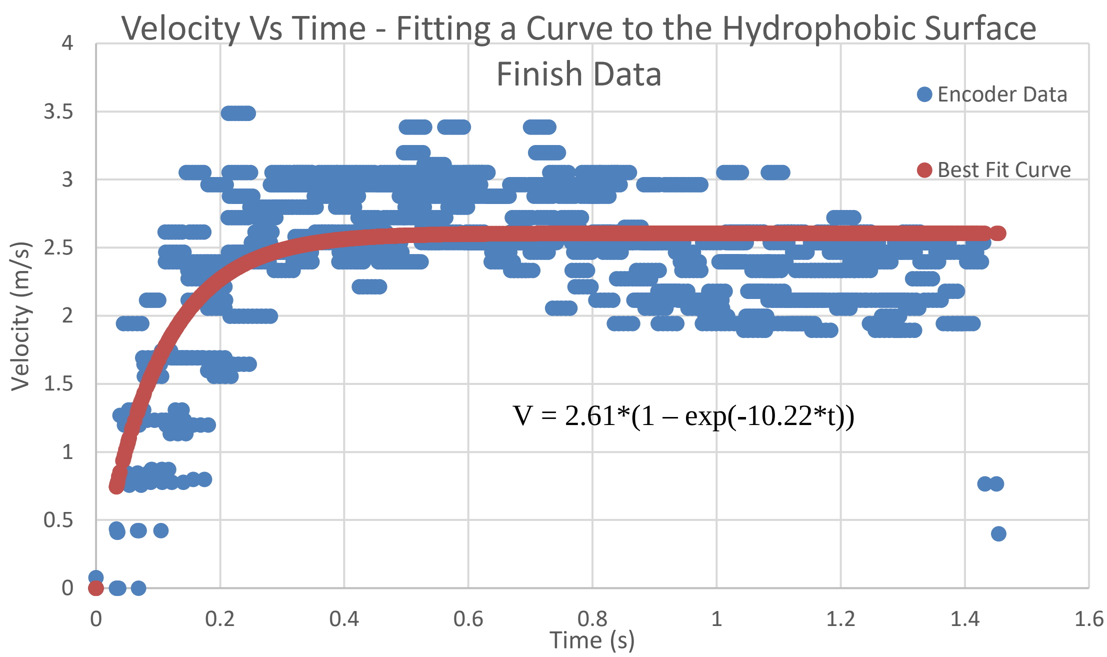


Figure 13: Fitting a Curve to the Data using Least Squares

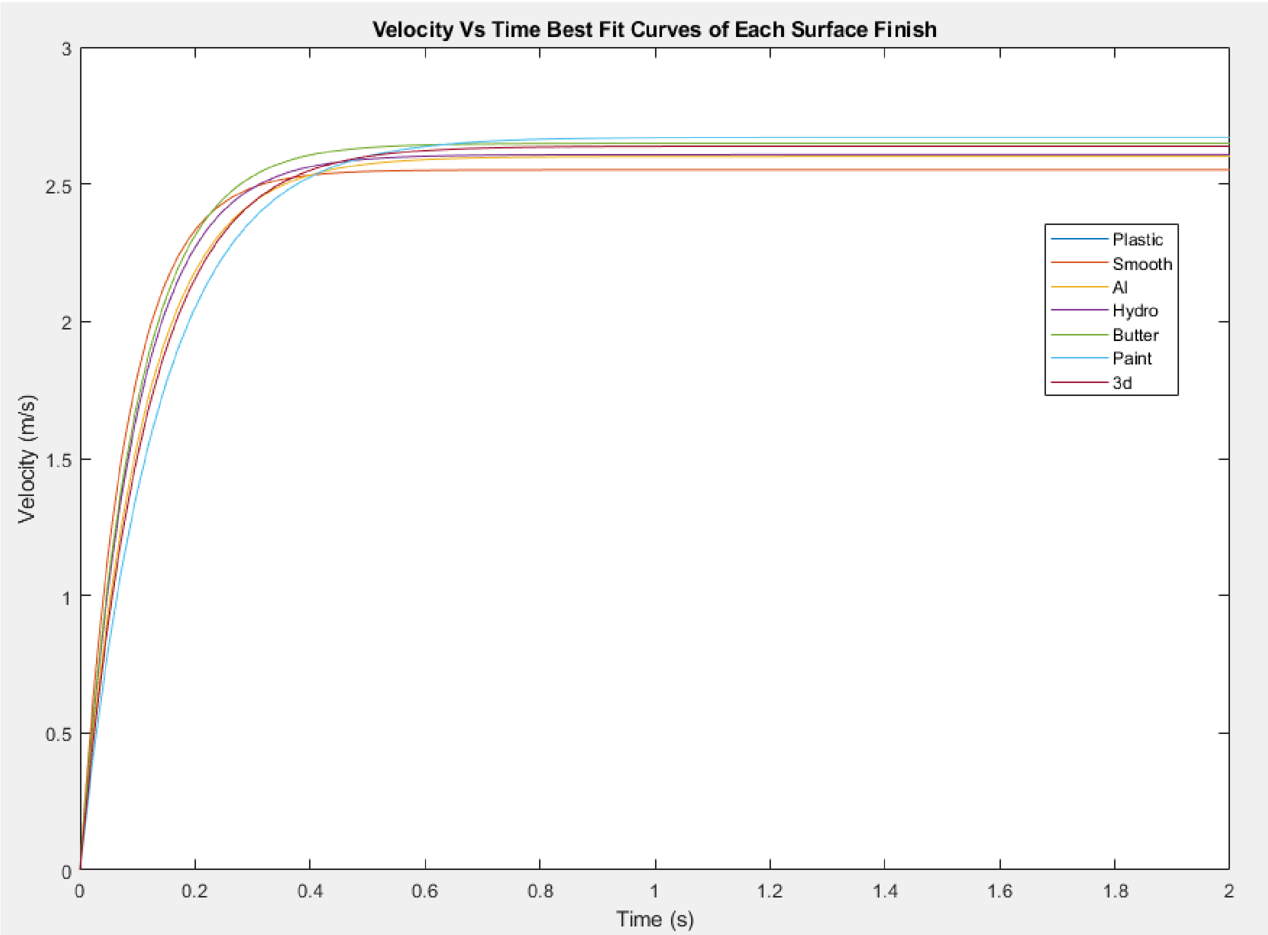


Figure 14: Comparing the Velocity Vs Time Best Fit Curves of Each Surface Finish

Table 6 below shows tabulated values of the A and B coefficients for each surface finish which were used in the final stages of our data processing.

Table 6: Tabulated Values of A and B coefficients for each Surface Finish

A and B Coefficient Values of Best Fit Velocity Curve							
Surface Finish	**Plastic Wrap**	**Smooth**	**Aluminum Wrap**	**Hydrophobic**	**Butter**	**Spray-Painted**	**3D-Print**
A	2.6383	2.5515	2.6002	2.6068	2.6480	2.6707	2.6383
B	8.4899	12.2597	9.1311	10.2180	10.3339	7.2884	8.4899

Next, we took the derivative of the best fit equation to find acceleration, which took the form:

$$Acceleration = A * B * exp(-B * t)$$

Using the acceleration and velocity equations, we were able to find the instantaneous Reynolds number and coefficient of drag which we will discuss further in the next section.

There is one issue that we will be discussing further in the Error Analysis section but will mention here briefly. There is some issue with the encoder that is causing it to consistently greatly overestimate the acceleration of the streamlined body. For example, the best fit line of figure 15 would have a max acceleration of A * B = 2.6068 * 10.218 = 26.7m/s^2, much higher than it should be, as seen in Table 3.

Finding Coefficient of Drag and Reynolds Number

Using the Drag Force, F_D derived in the previous section, we can find the instantaneous coefficient of drag for each surface finish.

$Instantenous\ Drag\ Force$:

$$= \frac{1}{2} * Density\ of\ Water * (Instantenous\ Velocity\ of\ Object)^2 * Cross\ Sectional\ Area\ of\ Object * Instantenous\ Coefficient\ of\ Drag$$

Rearranging the equation, we have:

$$Instantenous\ Coefficient\ of\ Drag = \frac{2 * Instantenous\ Drag\ Force}{Density\ of\ Water * (Instantenous\ Velocity\ of\ Body)^2 * Cross\ Sectional\ Area\ of\ Object}$$

$$= \frac{2 * Instantenous\ Drag\ Force}{Density\ of\ Water * (Instantenous\ Velocity\ of\ Object)^2 * \frac{\pi}{4} * (Diameter\ of\ Object)^2}$$

The diameter of the object is taken to be the diameter at the center of the 3D-printed part.

Next, the formula for Reynolds Number is shown below.

$$Instantenous\ Reynolds\ Number: = \frac{Density\ of\ Water * Instantenous\ Velocity\ of\ Body * Length\ of\ Object}{Dynamic\ Viscosity\ of\ Water}$$

These formulae are used in MATLAB (Refer Appendix C for the MATLAB Code) to plot the Coefficient of Drag against the Reynolds Number Graph for each surface finish as shown in Figure 15 below.

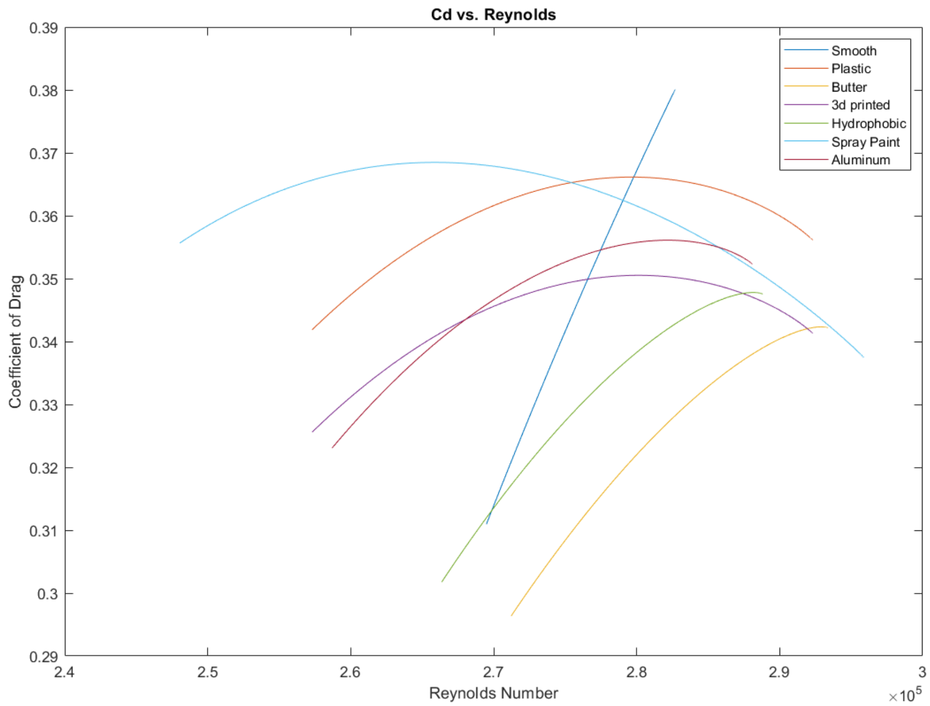


Figure 15: Coefficient of Drag against Reynolds Number for each Surface Finish

In general, we can rank the surface finishes from best performing (lowest drag coefficient) to worst performing as:

1. Butter
2. Hydrophobic
3. Smooth (Sanded Surface)
4. 3D Printed
5. Aluminum Foil
6. Plastic
7. Spray Paint

Looking at Figure 15, it is safe to conclude that butter has the lowest Drag Coefficient for the range of Reynolds Number in this plot. Its contender is the hydrophobic coating which is the green curve. For the rest of the surface finishes, the rank greatly depends on the range of Reynolds number, but the general trend is mentioned above.

The increasing trend of the curves suggests that the flow is in the transitional region going into the turbulent region. However, we deeply believe that the flow of the body when the experiment was conducted is laminar since the pool was only 8.4 feet deep and the body was allowed to travel for only 7 feet. Theoretically, this results in a laminar flow and creates an exponentially decreasing curve. To support this argument more strongly, we have found evidence that when the experimental maximum accelerations were roughly matched with the theoretical maximum accelerations, the curves were indeed decreasing exponentially.

We are certain that this huge variation is contributed by the acceleration data used from the encoder. As mentioned in the sources of error section, the experimental maximum accelerations are almost four times higher than the theoretical maximum acceleration. Despite having a major discrepancy in accelerations, the findings of this report are still valid because the data are processed similarly for each surface finish which results in the error being uniform across the data.

Prior to the experiment, we researched this topic and the summary is included in the introduction section. First of all, we can conclude that various surface finishes do affect the Coefficient of Drag of a streamlined body, as demonstrated by the difference in the curves in Figure 15. The lowest drag coefficients are butter and hydrophobic surfaces, which was what we were expecting considering the smoothening effect that they had on the body. Despite plastic wrap being expected to have a low drag coefficient, it had one of the worst performances compared to other finishes. The reason behind this might be due to how the body was wrapped in plastic. Since the body has a torpedo-like shape, it was very hard to smooth out the wrinkles in the plastic. All of our findings matched the predictions from the research paper.

Despite our findings showing that the butter coating and hydrophobic surface give the most promising result in reducing the coefficient of drag, care must be taken when using them to coat the bottom of any waterborne vessels. Studies have shown that vegetable oils have as much adverse effect on aquatic life, as petroleum products leak. We would recommend using fish oil to replace butter, as research has also shown that it reduces the drag coefficient of a body traversing through the water. On the other hand, hydrophobic spray products should be checked for their toxicity before using them for this purpose. It is our responsibility to ensure that we do not do more harm to the environment.

Statistical Analysis

The best way to identify whether there was a statistically significant difference between the 7 groups when it comes to the drag they experienced was to conduct an F-Test on the velocity data, which would measure the variance between groups compared to the variance amongst groups. We decided to use velocity because of its directly proportional relationship to drag.

We conduct hypothesis testing with a null hypothesis that:

$$H_0 = \text{There is no significant difference amongst groups}$$

So, the alternative hypothesis becomes that:

$$H_1 = \text{There is a significant difference amongst groups}$$

We chose $\alpha = 0.01$ and with this data, the two degrees of freedom were $DoF\ 1 = 6$ and $DoF\ 2 = 70$. Using this information and the FINV() function in Microsoft Excel, we determined that the critical F-value is $F_{cr} = 3.07$. To follow the procedure for the F-Test, we wrote a MATLAB script to calculate the F-statistic, which is included in Appendix D.

From this, we get that $F = 10.63$ and can see that:

$$F > F_{cr}$$

To visualize this on the F-distribution, consider the figure below.

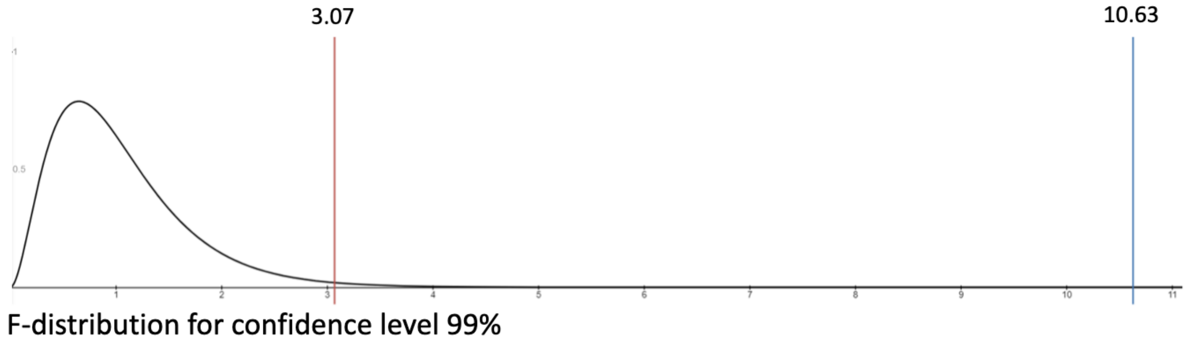


Figure 16: F-distribution for a confidence level of 99%

We can see that our calculated F-statistic is well within the reject region, so we can reject the null hypothesis, and accept the alternative hypothesis which states that there is a statistically significant difference amongst the groups.

Sources of Error

Looking at Table 3 in the Encoder Data Analysis section, we can see for every trial, we received several repeating time stamps for individual tick numbers. There were also several occurrences where the tick data would not be consistent and would advance one number and then move backwards one number, which indicates noise or error while the encoder was rotating. Using encoder terms this could possibly be explained by “bounce” which occurs when the mechanical components within the encoder physically bouncing back and contact the other side, giving a false reading in the other direction. This inconsistent data collection from the encoder most likely contributed to the uncertainty in our velocity calculations leading to odd-looking behaviours on our plotted diagrams.

Figure 17: KY-040 Rotary Encoder

Figure 18: A6B2-CWZ3E-1024 Rotary Encoder

For any future work using a rotary encoder, we would recommend using a higher quality encoder that would have a higher resolution and accuracy during rotation. The KY-040 Rotary encoder shown in Figure 10 uses a mechanical system with a resolution of 20 per revolution, and costs around $2.50 per encoder, whereas the A6B2 encoder uses an electronic system to track rotation and has a resolution of 1024 pulses per revolution but costs around $60.00 (RobotShop, 2020).

One possible source of error in our experiment could be the result of using string as the source of data transmission between the falling object in the pool and the rotary encoder that tracks the speed of the falling object. During downward acceleration we expect the string to perform as expected under tension, but if the object decelerates and the spool of thread continues to rotate from rotational inertia, we might have results that poorly reflect the instantaneous velocity of the object while moving through the water. Encoder error is not limited to only the data it generates. The way that it is mounted to the spool and apparatus has the potential for unexpected movement. Should the spool rotate by slipping, relative to the encoder, rotational speed would not be accurately captured.

During our experiment, we encountered issues with maintaining a straight path downwards during the dropping motion of the object. To counter this tendency for the object to stray from its intended path, the team attached a long narrow piece of wood to the back of the object, which gave a more consistent drop path. Although our trials were more or less consistent in the path, any small deviations in its path could result in small amounts of error, as the drag of the object would be much larger if the orientation of the object changes during the trial.

Another possible source of error during this experiment could be found in our approach to calculate acceleration. Using our data from the encoder, we determined distance travelled overtime to find velocity. Using the ten trials for each surface, as best fit model was used to determine a function of velocity, which we then derived an acceleration function by taking the derivative of the velocity function. The problem with this approach is the potential for compounding errors by extrapolating acceleration using incorrect velocity data.

Table 7 below shows the comparison between the theoretical maximum acceleration (see Table 4) and the experimental maximum acceleration obtained from the best fit velocity curve (see Figure 15).

Table 7: Theoretical Maximum Acceleration vs Acceleration from Best Fit Velocity Curve

Surface Finish	**Theoretical Maximum Acceleration**	**Experimental Maximum Acceleration**
Plastic Wrap	6.045	22.40
Smooth	6.040	31.28
Aluminum Wrap	5.957	23.75
Hydrophobic	5.939	26.64
Butter	5.973	27.36
Spray-Painted	5.980	19.46
3D-Print	5.951	22.40

As can be seen from the above table, the accelerations from the best fit velocity curve vary greatly from the theoretical maximum acceleration. As described in the previous section, the acceleration from the encoder should not exceed the theoretical because the presence of drag when the body falls through the water causes the acceleration to be lower than theoretical. Therefore, it is clear that the velocity and the acceleration plot do not reflect the actual condition when the experiment was conducted. Having said that, our findings from the experiment are still valid because the encoder data were analyzed similarly for all surface finishes and thus the values we have obtained are comparable to each other.

Conclusions and Recommendations

This report has discussed how surface roughness affects drag characteristics of a submerged body by testing out 7 easily accessible household materials and determining which one would reduce drag. By using statistical analysis procedures such as the least squares method allowed us to study the trend of how surface finishes affect drag, and we can see that smoother bodies experience less drag forces. In addition, we performed an F-test and found that there was a significant difference between the 7 surfaces when it comes to the drag they experienced. Our objective was met when we calculated the drag coefficients for each surface finish and found that the surface coated with butter had the lowest drag coefficient. The overall performance of surface finishes from best to worst is as follow:

1. Butter
2. Hydrophobic
3. Smooth (Sanded Surface)
4. 3D Printed
5. Aluminum Foil
6. Plastic
7. Spray Paint

If we were to repeat the experiment with the same budget and time constraints, we would have selected a more accurate encoder to get more reliable data as well as alter the orientation the streamlined body was 3D printed to see if the layer orientation plays a role when the body is falling in the water. However, without budget and time constraints, and access to more resources such as the UBC Aerolab, we would recommend conducting the experiment in UBC's wind tunnel that has a force measurement device attached to it. This will not only allow for more accurate data collected but also allow us to test wind speeds ranging from 0-35m/s and study the behaviour of the different surface materials in a wider range of Reynold's number. Another experimental procedure we recommend is doing a horizontal pull test with a buoyant object. Although the experimental setup would be more complex, it will help normalize gravity effects and give a better representation of canoeing in lakes and rivers. Finally, if given the luxury of time, we would increase the number of trials performed to further minimize random errors, repeat the experiment over 2 days to test its repeatability and explore a wider variety of surface finishes.

Personal Contributions and Reflections

Raymond Cardinal

Since I was the only member of the team that was not located in Vancouver, I was unable to participate in building the apparatus or participating in the physical collection of the data for this experiment. As such, my primary role for the project was to help organize and interpret the data. Being that I was not actively involved in a great deal of the setup, it was difficult for me to understand the results, as a lot of small details of the experiment were not clear through pictures and short videos alone. My initial task was mostly sorting through the trial data to separate out the time information, as the time stamp data was written into the same cells as the tick data. Once the data was cleaned for better use, I attempted to create Matlab code that could change the data into displacement, velocity and acceleration plots. This proved to be very difficult as the data was hard to interpret. Another role I helped with was finding the effect of buoyancy on our trial objects. The rest of my roles varied mostly in support of creating the report and helping rewrite the code. My thought process behind our experiment was to better understand how thin chemical layers play a role in drag versus surface roughness, and so I suggested we try a hydrophobic spray as well as some kind of paint layer. From the experiment, we did learn that chemical layers can play a more significant role in drag than originally thought. For future 305 students, I would suggest having some kind of basic flow chart diagram that would lay out a clear planning process required for the experiment and more clarity on what kind of data analysis is expected.

John Matheson

I performed several tasks while working on the capstone project. First, I designed and built the apparatus we used during the lab using a woodworking shop I have access to. Second, I took part in the data collection that spanned 3 days. Third, Ray and I turned the raw encoder data into displacement and velocity. Also, I calculated the least-squares equations to find the velocity best fit lines and acceleration constants. Furthermore, Audrey and I created the alternative experiment we suggested during our presentation. Lastly, I wrote a portion of the results section and all the “Calculating Velocity and Acceleration” section of the final capstone report. I originally suggested the idea for this experiment as I wanted to know if there was an easy way to make canoeing a little easier. I wanted to test various easily accessible materials to modify the surface finish of a streamlined object and see if there would have a significant decrease in drag. I am proud of the work I put into this experiment, my only regret about this project is not buying a more accurate encoder, because I think everything else went quite well. I think the professors did an excellent job given the current situation.

Aisyah Mohamed Lupi

My role in this project has been to contribute as best as I could to ensure that the project could be executed to its maximum potential. Prior to the experiment day, I assisted in writing the abstract and the proposal. After the proposal was approved, I recommended the venue to hold the experiment and was in charge in ensuring that the experiment would run smoothly for all trials at the venue. When the experiment was conducted, I helped setting up the pulley system to drop the streamline bodies, prepared the various finishes of the bodies and retrieved parts that fell in the pool. Most importantly, I ensured that the data (except the encoder's data) was well-collected by writing, taking pictures and video-recording everything. They were then uploaded to Google Drive for everyone's easy access. In addition, I was the person-in-charge for ensuring that our expenses did not exceed the $150 budget by creating an Excel Sheet to keep track of the expenditures.

In preparation for the presentation day, I took charge in preparing the first slide. We bounced off ideas on what to include for the next few slides. I instantly took over the net force calculations and continued coding on MATLAB to calculate the instantaneous drag coefficient and Reynold's number. It took us a few days to get the result, even after the presentation day, but it was worth it.

During the report-making, I wrote the Finding the Coefficients of Drag and Reynolds Number Section, Net Force calculation and theoretical maximum calculation in addition to comparing it with the experimental maximum acceleration. Furthermore, I inserted various tables and figures into the report before editing the it with my teammates.

In conclusion, I considered this experiment to be a success. Even though the data was very troublesome and we spent the majority of the time deciphering it, the team worked together to comb through the issue and finalize the findings. I could not have been prouder with my teammates. I learned a lot from this project and would do it all over again in a heartbeat. In terms of future years planning of MECH 305/6, I would suggest for more involvement with the team advisor. This could be achieved by setting up compulsory time period in the schedule to meet up with the Professor/TA instead of arranging it manually. We had two very effective meetings with our advisor and I wish we had more of it.

Ahijit Banerjee

Our idea behind this experiment was to try and reduce the effort required in rowing a canoe. We were particularly interested in this idea as most of our team members were interested in water sports such as rowing and canoeing and the experiment was safer than the alternative ideas we had generated.
In this experiment I worked on setting up the encoder, its code and circuit with Anmol to ensure that it collected data effectively. I also performed several tests to try and determine how the output of the data could be translated to physical quantities and identified key limitations in the encoder. Initially, I had assumed the encoder output would have a linear relationship to displacement but with repeated testing I found that the conversion factor between the encoder output and displacement was a function of how fast the encoder knob turned which greatly hindered our ability to effectively process the data. I also helped the team to setup the equipment and collect data over the three days of the experiment. Performing the experiment in an outdoor pool did pose its own issues where extreme care had to be taken to ensure that our open circuits remain dry in the rain. In the report, I worked primarily on the Methods section while working with Ray to setup the equation for our preliminary analysis of the data. Having access to the resources available as UBC would help significantly improve the quality of the data collected by using higher resolution encoders and allow us to easily perform the experiments. We faced several setbacks along the way when things did not work out according to our initial plan but working together as a team and ensuring that we clearly communicated helped us resolve the issues that arose quickly. I would recommend future MECH 305 students to perform their experiments early so that they can fail hard earlier in the process and update their timelines accordingly.

Audrey Alianto

As someone who enjoys kayaking and canoeing leisurely, I was interested to find ways that could decrease the effort needed when paddling. For this capstone project, I worked closely with John on the CAD model of the body and was responsible for 3d printing the streamlined bodies since I was the only one who had access to a 3d printer. Our design had a hollow center because we wanted to add weight to the 3d printed parts to ensure it sinks, and the additional wooden stick placed at the tail was to help with stability when the object was falling. I was also one of the 5 members who got together to setup and perform the experiment over 3 days. Having performed several runs of the experiment, there were numerous challenges that we faced such as the cold and rainy weather in Vancouver and having to prevent our electronic components from getting wet, as well as trying to find a more efficient way to reel in the fishing line since that was the most time-consuming part of our experiment. For the report, I worked on the conclusions and recommendations section and helped adjusting parts of the MATLAB code used to obtain a Cd vs. Re plot. Overall, I am happy with how the experiment turned out and the results we were able to get from it and will definitely try out adding a hydrophobic solution to the hull of my kayak over the summer. If given the opportunity to do the project again, I would look into performing a horizontal pull test instead, in order to better mimic the movement of a canoe. For future years in Mech 305/6, I would recommend taking the time to think of possible failure modes and come up with solutions for them as this will save a lot of time when performing the experiment itself. Also, always start your experiment as early as possible to account for any unexpected challenges along the way.

Anmol Bhatia

I was in charge of various aspects in all stages of this project. I started by researching and reading literature available online to get some sense of what we expect from our experiment. As for the actual experiment, Ahijit and I worked together frequently to set up the Arduino, its code and the encoder, along with its circuit. This was a crucial part of the experiment, as all of our data was gathered by the encoder. In addition to this, as a part of the analysis, I wrote a MATLAB script to conduct an F-Test to show that there was a statistically significant difference between the groups. I also wrote the Abstract, Introduction, Setup part of the Methods section and the F-Test discussion in this report. We decided to conduct this experiment in water because we wanted to study drag characteristics in water, but this could have been executed better. Having conducted the experiment outside, there were several challenges we faced, including the cold weather, rain and the fact that our parts kept falling in the deep end of the pool. As mentioned in our presentation, this experiment could have been done a lot better and much more reliably using equipment available at UBC's mechanical engineering labs, such as a wind tunnel and more sensitive encoders. Overall, I felt that this project was an excellent opportunity to experience data analysis in an experimental context and I enjoyed this challenge. For the future, I think the students are more likely to succeed with increased involvement from their advisors. Of course, this year we were limited to remote communication but I think face-to-face meetings would really help out.

Acknowledgements

Our team wishes to extend our thanks to the instructors and teaching assistants of MECH305/306 for their dedication in adapting this course for online delivery and being accommodating with our concerns about deadlines and deliverables during this unconventional semester. Additionally, we are grateful for the opportunity to work closely with Dr. Steven Rogak on this project and for his dependable advice and steady guidance during team meetings.

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Appendices

Appendix A – Arduino Script for the Rotary Encoder

```
// Declaring variables //
int A;
int B;
int r = 0;
unsigned long myTime;

// Setup Function //
void setup()
{
  // Setting up the interrupt pin and button //
  attachInterrupt(0, STEP, CHANGE);
  attachInterrupt(1, BUTTON, CHANGE);

  // Setting up input pin //
  pinMode(4, INPUT);

  // Serial port initialization //
  Serial.begin(9600);
}

// Main function //
void loop()
{

}

// Function to compare the values of A and B as the encoder rotates //
void STEP()
{
  // Read values //
  A = digitalRead(2);
  B = digitalRead(4);

  // Compare values //
  if(A != B)
  {
    // Incrementing //
    r++;
  }else
  {
    // Decrementing //
    r--;
  }

  // Printing value to serial monitor //
  Serial.println(r);


}

// Although the button function was not applicable to our experiment, it is needed for the
program to run //
void BUTTON()
{
  if(digitalRead(3) == HIGH)
  {

  }else if(digitalRead(3) == LOW)
  {

  }
}
```

Appendix B – MATLAB Script used for Plotting Cd vs Re Graph, Velocity vs Time Graph

```
% MECH 305 - CAPSTONE Project
% March 2021
% Team 7
% This script calculates Reynolds, Cd, etc

% Calculate Reynolds, Cd, etc

clc;clear;

% Constants
g = 9.81;
v1 = 9.65198*10^-6;  % Volume of stick
v2 = 0.00010492;     % Volume of piece
Dens_w = 999.1;      % Density of water at 15 Celcius
length_part = 0.145; % Length of object
r = 0.02;            % Central Radius of object
Area = pi*r^2;       % Central Area of object
mu = 1.3076*10^-3;   % Dynamic Viscosity of Water at 15 Celcius kg/m*s


% List of mass of object and stick
m_smooth = 0.2728;
m_plastic = 0.2731;
m_butter = 0.268;
m_3d = 0.2665;
m_hydro = 0.2656;
m_paint = 0.2685;
m_alum = 0.2669;


m_all = [m_smooth;m_plastic;m_butter;m_3d;m_hydro;m_paint;m_alum]
```

```
% Time
t = 0.25:0.001:1.5


% A and B Coefficients for each surface finish
A = [2.55152; 2.63836; 2.64804; 2.63836; 2.60686; 2.67072; 2.60027];
B = [12.25965702; 8.48993991; 10.33396603; 8.48994214; 10.21800426; 7.288418211;
9.131166213];


for i = 1:length(m_all)


acc(:,i)= A(i)*B(i)*exp(-B(i)*t);
Vel(:,i) = A(i)*(1-exp(-B(i)*t));


% Reynold Number


Re(:,i) = (Dens_w*Vel(:,i)*(length_part))/mu;
Ret(:,i) = (Re(:,i))';




x(:,i) = (Ret(:,i));


% Gravitational Force for stick and object
Fg(:,i) = m_all(i).*g;


% Bouyancy Force for stick and object
Fb_stick(:,i) = Dens_w.*v1.*g;
Fb_object(:,i) = Dens_w*v2.*g;
```

```
Fdrag(:,i) = Fg(:,i) - Fb_object(:,i) - Fb_stick(:,i) - m_all(i).*acc(:,1);


% Coefficient of Drag
Cd(:,i) = (2*Fdrag(:,i))./(Dens_w*(Vel(:,i)).^2*Area);
Cdt(:,i) = (Cd(:,i))';


y(:,i) = (Cdt(:,i));


end


plot(x,y) % Cd against Re
title('Cd vs. Reynolds');
xlabel('Reynolds Number');
ylabel('Coefficient of Drag');
legend('Smooth','Plastic','Butter','3d printed','Hydrophobic','Spray
Paint','Aluminum');
```

Appendix C– MATLAB Script used for F-Test

```
% MECH 305 - CAPSTONE Project
% March 2021
% Team 7
% This script runs the F-test to find the F-statistic and the degrees of
% freedom

% Number of different samples %
numData = 7;

% Isolating the velocities %
V_final_Aluminum=V_final_Aluminum(:,1);
V_final_Butter=V_final_Butter(:,1);
V_final_Hydrophobic=V_final_Hydrophobic(:,1);
V_final_Paint=V_final_Paint(:,1);
V_final_Plastic=V_final_Plastic(:,1);
V_final_3DFinish=V_final_3DFinish(:,1);
V_final_Smooth=V_final_Smooth(:,1);

% Removing invalid values %
V_final_Aluminum=(V_final_Aluminum(~isnan(V_final_Aluminum)));
V_final_Butter=(V_final_Butter(~isnan(V_final_Butter)));
V_final_Hydrophobic=(V_final_Hydrophobic(~isnan(V_final_Hydrophobic)));
V_final_Paint=(V_final_Paint(~isnan(V_final_Paint)));
V_final_Plastic=(V_final_Plastic(~isnan(V_final_Plastic)));
V_final_3DFinish=(V_final_3DFinish(~isnan(V_final_3DFinish)));
V_final_Smooth=(V_final_Smooth(~isnan(V_final_Smooth)));

V_final_Aluminum=(V_final_Aluminum(~isinf(V_final_Aluminum)));
V_final_Butter=(V_final_Butter(~isinf(V_final_Butter)));
V_final_Hydrophobic=(V_final_Hydrophobic(~isinf(V_final_Hydrophobic)));
V_final_Paint=(V_final_Paint(~isinf(V_final_Paint)));
V_final_Plastic=(V_final_Plastic(~isinf(V_final_Plastic)));
V_final_3DFinish=(V_final_3DFinish(~isinf(V_final_3DFinish)));
V_final_Smooth=(V_final_Smooth(~isinf(V_final_Smooth)));
```

```
% Isolating number of enteries %
n_al = height(V_final_Aluminum);
n_butter = height(V_final_Butter);
n_hydro = height(V_final_Hydrophobic);
n_paint = height(V_final_Paint);
n_plastic = height(V_final_Plastic);
n_3D = height(V_final_3DFinish);
n_smooth = height(V_final_Smooth);

% Total number of enteries %
N = n_al + n_butter + n_hydro+ n_paint+n_plastic+n_3D+n_smooth;

% Calculating the sum of the squared %
sum_al = sum(V_final_Aluminum(:,1));
sum_al_sq = sum((V_final_Aluminum(:,1)).^2);
sum_butter = sum(V_final_Butter(:,1));
sum_butter_sq = sum((V_final_Butter(:,1)).^2);
sum_hydro = sum(V_final_Hydrophobic(:,1));
sum_hydro_sq = sum((V_final_Hydrophobic(:,1)).^2);
sum_paint = sum(V_final_Paint(:,1));
sum_paint_sq = sum((V_final_Paint(:,1)).^2);
sum_plastic = sum(V_final_Plastic(:,1));
sum_plastic_sq = sum((V_final_Plastic(:,1)).^2);
sum_3DFinish = sum(V_final_3DFinish(:,1));
sum_3DFinish_sq = sum((V_final_3DFinish(:,1)).^2);
sum_smooth = sum(V_final_Smooth(:,1));
sum_smooth_sq = sum((V_final_Smooth(:,1)).^2);

% Finding variance between groups %
SS_bet = sum_al^2/n_al + sum_butter^2/n_butter + sum_hydro^2/n_hydro +
sum_paint^2/n_paint + sum_plastic^2/n_plastic + sum_3DFinish^2/n_3D +
sum_smooth^2/n_smooth -
(sum_al+sum_butter+sum_hydro+sum_paint+sum_plastic+sum_3DFinish+sum_smooth)^2
/N;
S_bet_sq = SS_bet/(numData-1);

% Finding variance within groups %
```

```
SS_al = sum_al_sq - sum_al^2/n_al;
SS_butter = sum_butter_sq - sum_butter^2/n_butter;
SS_hydro = sum_hydro_sq - sum_hydro^2/n_hydro;
SS_paint = sum_paint_sq - sum_paint^2/n_paint;
SS_plastic = sum_plastic_sq - sum_plastic^2/n_plastic;
SS_3D = sum_3DFinish_sq - sum_3DFinish^2/n_3D;
SS_smooth = sum_smooth_sq - sum_smooth^2/n_smooth;

SS_within = SS_al + SS_butter + SS_hydro + SS_paint + SS_plastic + SS_3D +
SS_smooth;
S_within_sq = SS_within/(N-numData);



% Displaying results %
DOF1 = numData - 1
DOF2 = N - numData
F = SS_bet/S_within_sq
```

Appendix D – KY-040 Data Sheet (RCS Components, n.d.)

The KY-040 rotary encoder is a rotary input device (as in knob) that provides an indication of how much the knob has been rotated AND what direction it is rotating in. It's a great device for stepper and servo motor control. You could also use it to control devices like digital potentiometers.

SKU: ASS-1058

Brief Data:

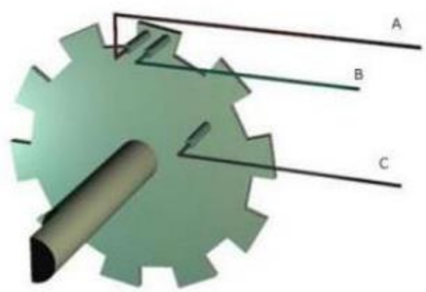
- Operating voltage: 5V.
- Pulses/360° Rotation: 20.
- Output: 2-bit gray code
- Mechanical Angle: 360° continuous.
- With built in push button switch (push to operate)
- Dimensions: (30 x 18 x 30) mm.
- Compatible with Arduino/Raspberry Pi controller board.

A rotary encoder has a fixed number of positions per revolution. These positions are easily felt as small "clicks" you turn the encoder. The KY-040 module has thirty of these positions. On one side of the switch there are three pins. They are normally referred to as A, B and C. In the case of the KY-040, they are oriented as shown. Inside the encoder there are two switches. Once switch connects pin A to pin C and the other switch connects pin B to C.

In each encoder position, both switches are either opened or closed. Each click causes these switches to change states as follows:

- If both switches are closed, turning the encoder either clockwise or counterclockwise one position will cause both switches to open
- If both switches are open, turning the encoder either clockwise or counterclockwise one position will cause both switches to close.

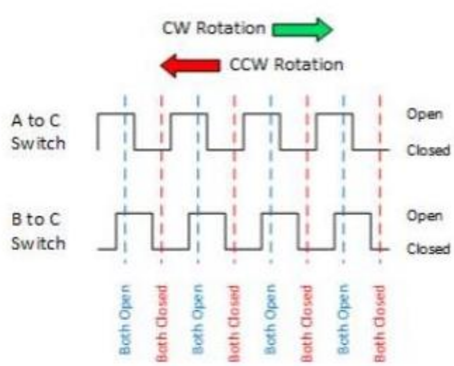
The illustration below is representative of how the switch is constructed.



As you can see, the angular position of the A terminal and the B terminal is such that:

- Rotating the switch clockwise will cause the switch connecting A and C to change states first.
- Rotating the switch counterclockwise will cause the switch connecting B and C to change states first.

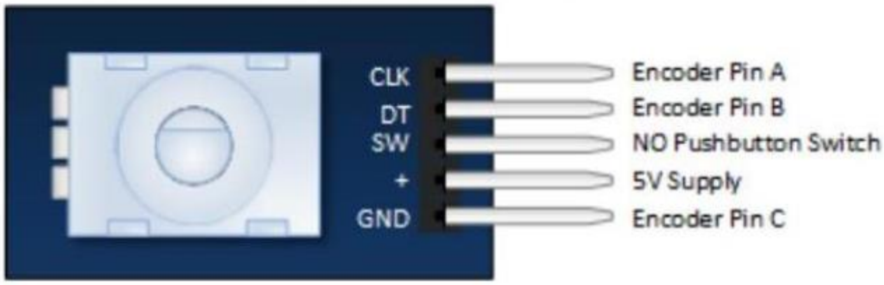
If we were to represent the opening and closing of the switches as wave forms, it would look something like this.



Essentially, determining which switch changed states first is how the direction of rotation is determined. If A changed states first, the switch is rotating in a clockwise direction. If B changed states first, the switch is rotating in a counter clockwise direction.

Pin Assignment:

The pin outs for this rotary encoder are identified in the illustration below.



The module is designed so that a low is output when the switches are closed and a high when the switches are open. The low is generated by placing a ground at Pin C and passing it to the CLK and DT pins when switches are closed. The high is generated with a 5V supply input and pull-up resistors, such that CLK and DT are both high when switches are open. Note previously mentioned is the existence of a push button switch that is integral to the encoder. If you push on the shaft, a normally open switch will close. The feature is useful if you want to change switch function. For example, you may wish to have the ability to between coarse and fine adjustments.

Rotary Encoder Schematic: