

# Candidate 2 evidence

## Outline

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#### *Project aim*

Many firefighters face significant risks and dangers when responding to emergency situations. This is often due to obstacles, collapsing structures, and dense smoke. Frequently, they encounter situations where fires occur in spaces which are either too small for firefighters to access, or they are completely obstructed by other structures. These small inaccessible areas often pose significant challenges to firefighters. Additionally, fires that ignite in these small compartments can quickly escalate, spreading to adjacent areas and if firefighters are unable to access these areas, the risk can be drastically increased. Moreover, firefighters cannot simultaneously focus on extinguishing the major fires in the buildings, and attempt to dangerously climb into really small areas where the fire might cause later risk by spreading to other areas.

The aim of this project is to reduce the amount of injuries that occur for firemen by developing a compact remotely operated fire extinguishing vehicle which would be able to get into these small compartments to extinguish the fires or stop the spread of further fires. This would also allow the firemen to focus on the larger fires in large areas meaning by the time the firemen finally get to the small areas, the spread of fire from those areas would have already been stopped.

#### *Objectives and Methodology*

The objective of this project is the development of this vehicle. Here is a list of the estimated short term objectives. The objectives will most likely change as the project progresses.

- Carry out Initial research
- Carry out calculations from the initial research
- Mathematically model all mechanical systems
- Mathematically model all structural systems
- Mathematically model all electronic systems
- Mathematically model and program all control systems
- Simulate major systems of the project
- Construct a prototype of the finished project

Approximate timings and tasks for the project:

- Carry out initial research into the project:

This should take approximately 1 month to complete. A lot of research must be carried out before embarking on this project. Some of the research that could be done is: carrying out research into fires, fire hoses, materials and fire trucks; researching mechanical systems and selecting suitable motors for all the mechanisms; researching ways of remotely controlling the vehicle and researching the video feedback.

The research could be done by simply reading journals, articles, googling, or looking for information online. The major advantage of this method of research is that it is very quick and would give the required information for the project to be continued. However, another method of researching would be physically testing aspects of the project or asking professional advice. The advantage of this method is that it would allow you to get a much better understanding of the issue, although it would take much longer.

- Mathematically model all mechanical and structures systems:

This should approximately take 2 months to complete. Calculations for all of the mechanical systems should be carried out in this section. This section would include: calculating all the forces acting on the vehicle; calculating the required torque for all motors; creating a design of the vehicle; modelling and carrying out all calculations of a system such as the drive axle.

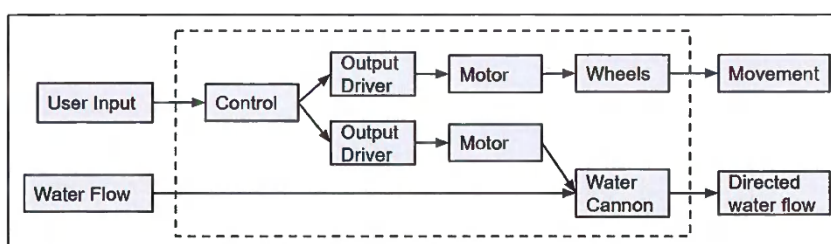
- Mathematically model all electronic and control systems:

This section should approximately take 2 months to complete. Calculations for all electronic systems should be carried out, and programming of all the control systems. This section will include: programming the communication between the vehicle and the operator's device, programming the video feedback, programming control, calculating circuit values, and designing an electronic circuit.

- Simulation and construction of the vehicle:

This section should take approximately 2 months to complete. In this section, the mathematically modelled systems from the previous sections should be tested, this can be done by either simulating certain parts of the vehicle, or constructing a model of the vehicle or the vehicle itself. The main advantage of simulation is that it is much quicker to do, however, it might not be entirely accurate as real life considerations are not taken into account. The advantage of the real life construction of the vehicle is that it would allow the vehicle to be properly tested, everything can be tested at once, and it would be much more interesting to create a working prototype, however, this would be a very long process which might not be completed in time.

**Initial Analysis**



The main inputs in this system would be the user input for controlling the movement of the vehicle, and the water flow from a fire hydrant. The main outputs of this system would be the movement of the vehicle, and the jetting water in the required direction.

**Outline Specification**

The vehicle should be operated remotely by some sort of application used by the user. The vehicle should have a camera which would stream video to the application so that the user would be able to control the vehicle. The vehicle should be able to withstand the temperatures inside a burning building. The vehicle should also have the right motors and torque to traverse at the right speed. The vehicle must be able to carry around with it a fire hose which would get its water supply from a fire hydrant or other means. The vehicle must extinguish fires.

**Resource Requirements**

The following are the main resources required for this project:

- Strong materials which will survive hot environments for the body of the vehicle
- Fireproof wheel materials
- Arduino microcontroller and other electronics which may be required after research
- Suitable battery
- Motors, servos, and gears for the mechanisms
- Fire hose and suitable nozzle
- Fire hydrant or connection to a water supply
- Device and software to program control or simulate sub systems

Some of these resource requirements could be really difficult or expensive to acquire especially in the limited timeframe as the project must be completed in March 2024. For these reasons I think it would be impossible to build the actual vehicle, instead, a model of the vehicle or different ways to simulate different parts of the vehicle should be done.

I think that in order to get a better understanding of the project and to dedicate more time to the simulation and mathematical modelling of the project, the research stages of the process should be completed by the start or middle of November 2023. To help with research and to suggest advice I have contacts with experts in the field from Heriot Watt University.

# Research, analysis and specification

## Research, Analysis and Specification

### Analysis

The bridge will require three major sub-systems which are the main structure, the gear mechanism to allow the bridge to extend and retract and an electronic control system to control when the bridge extends or retracts. The main structure will have to be strong enough to hold the weight of the average pedestrian traffic with a high factor of safety to account for additional weight of objects and unpredictable weight of pedestrians on the bridge. The retracting mechanism will require a compound gear train to create a high enough velocity ratio along with a system to connect the gear train to the main structure without causing damage to the gear train during the retraction or extension. The control system will require a set time limit for the intervals between retracting and extending and a manual override to change the state of the bridge in an emergency.

### Research Strategy

The structure design will require information on the weight of the pedestrians crossing the bridge, the design of cable-stayed bridges and an already existing bridge with a similar design to this project. The retracting mechanism will also require information on an already existing bridge with a similar design to this project. The control system will require information on creating a PWM signal. The required information will be found through careful internet research and fact checking found information against multiple sources.

### Research

#### Hörn Bridge

The Hörn bridge in Kiel, Germany is a folding bridge made of three sections separated by hinges that uses a similar design to this project. The bridge was designed to allow ships to sail down the Kiel while also allowing pedestrians to cross the fjord. The folding mechanism uses two hydraulic motors connected to winches to pull a pair of mast towers that are anchored at the end of the bridge. The first tower is connected to the hinge between the first and second sections and the second tower is connected to the hinge between the second and third sections of the bridge. During folding, cables attached to the deck of the bridge pull the third section up as they are pulled by the mast towers creating an N shape when it is fully folded. The bridge requires a time of 2 minutes to complete the folding or unfolding process.



Figure 1: Hörn bridge during the folding process  
(schlaich bergemann partner, no date)

### Structure Design

The primary component of the structure is the cables and towers resulting in a cable-stayed bridge design. A cable-stayed bridge uses diagonal cables to transfer the vertical loads on the bridge to the towers. The towers then transfer the vertical loads into the foundation. At the tower the horizontal components of the cable forces from the main span are in equilibrium with the horizontal forces from the side span. The compression force in the deck girder due to the horizontal component of the cable force can be calculated using the formula:

$$P_{ci} = \frac{P_{vi} \times L_i}{H_t}$$

$P_{ci}$  is the compression force in the deck girder

$P_{vi}$  is the total vertical loads at the cable connection

$L_i$  is the horizontal distance to the tower

$H_t$  is the height of the cable connection at the tower above the deck

## Pulse Width Modulation

Pulse width modulation or PWM is a method of controlling the speed of a motor by using a series of on (mark) and off (space) pulses and varying the ratio of mark time to space time. An increase to the mark time will cause the motor to rotate faster and a decrease to the mark time will cause the motor to rotate slower.

A PWM signal can be produced by using an Astable 555 Oscillator circuit as shown in Figure 2. Within the circuit  $R_A$  is resistor R1 and the top half of potentiometer VR1 and  $R_B$  is resistor R2 and the bottom half of potentiometer VR1. This circuit works by charging and discharging the capacitor C with the current flowing through the timing networks  $R_A$  and  $R_B$ . During the charging process the energy to charge the capacitor flows through network  $R_A$  but gets diverted around network  $R_B$  and flows through D1 instead. As soon as the capacitor is charged it switches to the discharging process and is discharged through D2 and network  $R_B$  into pin 7. As soon as the capacitor is fully discharged the process repeats to produce a PWM signal.

The mark and space times can be calculated using the equations shown below:

$$\text{Mark time} = 0.693(R_A) \times C$$

$$\text{Space time} = 0.693(R_B) \times C$$

The total time for a single cycle is equal to the mark time plus the space time.

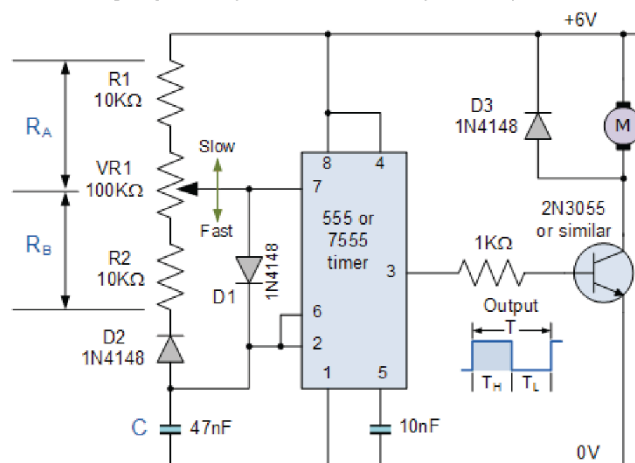


Figure 2: Astable 555 Oscillator circuit (Electronics Tutorials, no date)

## Specification

### Sub-systems

#### Bridge Structure:

- Initial UDL of  $1400 \text{ Nm}^{-1}$  from pedestrians acting on deck girders.
- Structure has a full length of 30m
- Force of pedestrians and load of  $3200 \text{ Nm}^{-1}$  from full weight of structure acting on cables.
- Force on cables transferred into foundations through cable towers.
- Force from weight of structure and additional force of  $4500 \text{ Nm}^{-1}$  from folding mechanism are acting on the cables and towers during folding of the bridge.

#### Folding Mechanism:

- The first tower is connected to the hinge between the first and second sections of the bridge.
- The second tower is connected to the end of the third section of the bridge.
- As the towers are being pulled the sections will fold into an N shape through hinges between each section.
- Uses winches to pull cables attached to the two cable towers.
- Two winches on each side of the bridge.
- Each winch is connected to a cable tower with one winch per tower on both sides.
- The winches are powered by a compound gear train with a velocity ratio of (VR).
- The compound gear train is powered by a motor with a speed of 1200 revolutions per minute.
- The speed and direction of the motor are controlled by the control system.

#### Control system:

- The control system will use a microcontroller program to turn on the motor after a time of 30 minutes or when a manual override is pressed.
- The microcontroller will track the current state of the bridge which will be used to determine the direction of rotation of the motor.
- The speed of the motor will be controlled by a PWM system that uses an astable 555 oscillator circuit to produce the PWM signal.
- The direction of the motor will be controlled by a transistor based H-Bridge connected to the microcontroller.
- The motor will be turned off by using limit switches to track if the bridge is fully folded or unfolded.

### Safety Precautions

- Handrails will be required on the bridge.
- An alarm and lights system will be required to alert pedestrians to the bridge beginning to fold or unfold.
- Barriers will be required to prevent pedestrians from trying to cross the bridge when the bridge is unfolded.
- Lights will be required at the bridge ends and along the third section for visibility at night.

### Resources Required

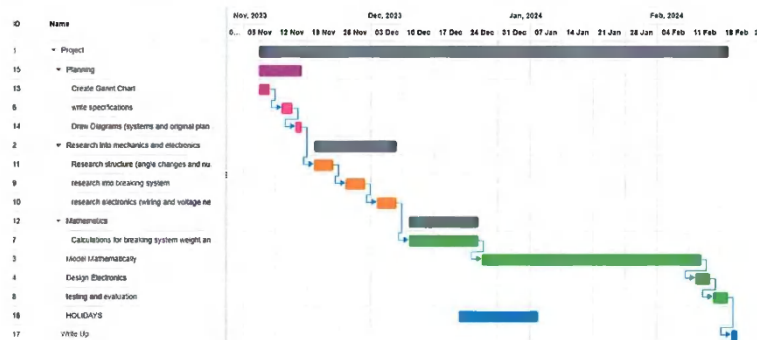
To construct the treadmill I will need materials such as wood and stainless steel for the frame and each part of the structure. For the circuits I will need to investigate the connection between the main body of the microcontroller and each subsystem. I will need capacitors, resistors, a 555 timer and a differential amplifier (Op Amp). I will also need to calculate specific data to ensure the system can operate effectively such as: the max bending moment of the top beam and its Young's Modulus value (a mechanical property of solid materials that measures the tensile or compressive stiffness when a force is applied lengthwise); and e.g., values of capacitance and resistance to have an adequate flash frequency for the system-operating LED.

# Production and maintenance of a detailed project plan

## Production and Maintenance of a Detailed Project plan

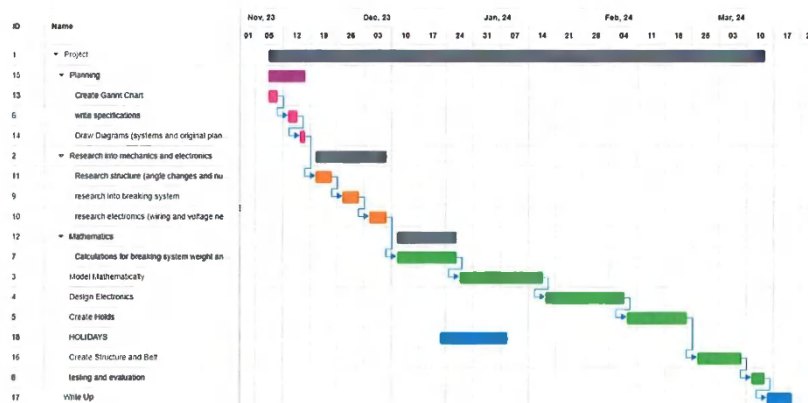
To create an effective plan firstly a Gantt chart was made. Gantt charts are often used to show a critical path, and to identify the longest duration of specific tasks needed to be undertaken to arrive at an overall schedule for the delivery of a project.

The chart below shows how I initially thought the process would progress:

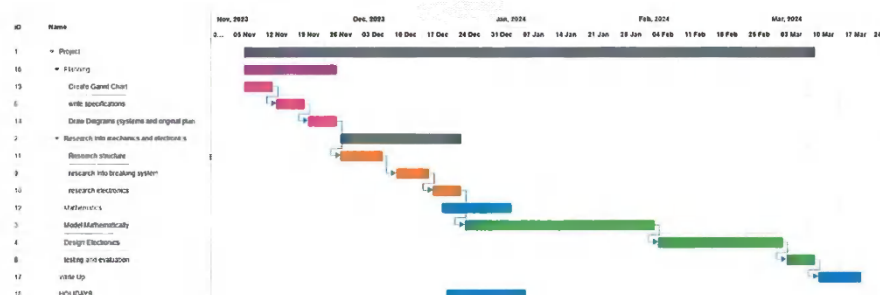


The chart above shows how my initial planning was incredibly optimistic for the efficiency of my working versus the time that we actually had to finish this project.

After we had been given a longer deadline (mid-March versus mid-February 2024) another Gantt chart was created to show how I thought I should use my time working on my project (see below). The updated final-hand-in date allowed a lot more time versus the original plan.



However, as I began to progress through the project I realised that I had again been overly optimistic with how much time was needed for e.g., research, and mathematical modelling. This meant that another reiteration of the Gantt chart was needed for the final project plan:



It is clear from the final chart that a few stages had to be removed including time previously allocated for creating climbing holds and creating the structure of the system too. This is because it took a lot longer to mathematically model the design of the climbing wall than I had originally anticipated. With some sections removed I instead decided to focus on the engineering of the belt as much as possible. While I would not be able to create the holds or make the actual belt, I have used the time to calculate, using my engineering knowledge, the rest of the values needed for the structure. This extra time was used for analysis and simulation, which in turn allowed me to see whether the values that I had calculated were correct and applicable.

The critical path shown above would be 15-2-12-17. This is because these points are the main headers for each subsection, showing that each step in this project is crucial.

To analyse the engineering of part of my project, the main resources that I require are software for simulation: such as SkyCiv and Yenka. This software is available to me through my school and the resources they have available to them. The simulation software will be needed as soon as I have completed the mathematical models.

For any potential construction of the climbing wall (or part of it) I would require wood, metal, a motor and some electronics including e.g., an Arduino microcontroller. These final components would only be necessary if the time permitted for this project is long enough that I can begin to physically construct and build a few parts of the proposed climbing treadmill wall.

# Mathematical modelling and analysis

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## Mathematical modelling and analysis.

### Structural Modelling of Subsystem 1: Propulsion System.

Calculating approximate force of drag and therefore required force from motors.

$$F_D = \frac{1}{2} C_D \rho V^2 A_{proj}$$

Equation 4

$$R_e = \frac{\rho V L}{\mu}$$

Equation 5

For the purposes of modelling, we can assume that the ROV is traveling at  $0.1 \text{ m s}^{-1}$ . The viscosity of water ( $\mu$ ) is taken as  $1 \times 10^{-3} \text{ Pas}$  (Wikipedia, 2023). The density of water taken as  $997 \text{ kg m}^{-3}$ .

$$R_e = \frac{997 \times 0.1 \times L}{1 \times 10^{-3}}$$

$$R_e = 99.7 \times 10^3 L$$

$$R_e = 0.997 \times 10^5 L$$

Equation 6

To calculate the coefficient of drag ( $C_D$ ) from the Reynolds number ( $R_e$ ) we can use one of the equations proposed by the paper titled "Drag Coefficient" (Polezhaev & Chircov, 2011). This paper derives equations for a sphere given a certain range of the Reynolds number. As previously mentioned, the main hull shape of the ROV can be approximated as an elongated sphere.

$$C_D = \frac{24}{R_e}, R_e < 0.2$$

Equation 7

$$C_D = \frac{21.12}{R_e} + \frac{6.3}{\sqrt{R_e}} + 0.25, 0.2 < R_e < 2 \times 10^5$$

Equation 8

If we take the length (L) to be 1 (or less) then  $R_e = 0.997 \times 10^5 < 2 \times 10^5$ , therefore Equation 8 can be used. We can rearrange Equation 8 as follows.

$$C_D = 21.12 R_e^{-1} + 6.3 R_e^{-\frac{1}{2}} + 0.25$$

Equation 9

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We can calculate the area as seen from the stream ( $A_{proj}$ ) as shown below. The diameter is taken as 125mm as this is a standard size of PVC tubing. We can recall from the research section that it was decided that the main body section should be constructed from this material.

$$A_{proj} = \pi r^2$$

$$A_{proj} = \pi \times 0.0625^2$$

$$A_{proj} = 0.0123m^2 \text{ (4dp)}$$

Equation 10

We can substitute Equation 9 into Equation 4 as shown to obtain an expression for the force of drag ( $F_D$ ).

$$F_D = \frac{1}{2}(21.12R_e^{-1} + 6.3R_e^{-\frac{1}{2}} + 0.25) \times 997 \times 0.1^2 \times 0.0123$$

$$F_D = 0.0613(21.12R_e^{-1} + 6.3R_e^{-\frac{1}{2}} + 0.25)$$

$$F_D = 1.29R_e^{-1} + 0.39R_e^{-\frac{1}{2}} + 0.015$$

Equation 11

We can then substitute Equation 6 into Equation 11 to obtain an expression for the force of drag ( $F_D$ ) in terms of length (L).

$$F_D = 1.29(99.7 \times 10^3 L)^{-1} + 0.39(99.7 \times 10^3 L)^{-\frac{1}{2}} + 0.015$$

Equation 12

We can now sub in for an estimated length of 550mm to finally obtain an approximation of the force of drag ( $F_D$ ).

$$F_D = 1.29(99.7 \times 10^3 \times 0.55)^{-1} + 0.39(99.7 \times 10^3 \times 0.55)^{-\frac{1}{2}} + 0.015$$

Equation 13

Solving this equation we can get the approximate force of drag at  $0.1ms^{-1}$ .

$$F_D = 0.02N \text{ (2dp)}$$

Equation 14

This is only a very rough approximation of drag experienced by the ROV, only taking into account the area of the main body tube. This approximation is fine for the purpose however as this provides a baseline force the motors must output to overcome drag. To add some room for extra potential acceleration and to account for extra drag from the motors as well as frictional drag which was not modelled the force outputted from the motors has been rounded up to  $0.5N$  per motor.

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## Nodal analysis

An approximation of the internal support structure of the radial motor support is shown below in Figure 15. The 0.5N represents the force from the motors as calculated in the previous section. Estimates of reaction force location and direction are also shown.

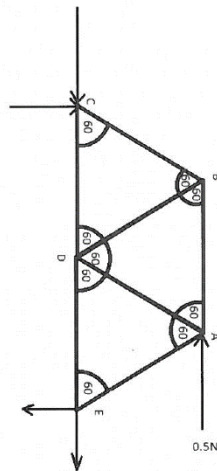


Figure 15

It was worked out which members would be in compression and which ones would be in tension. This is shown below in Figure 16. The arrows show the internal forces in the member.

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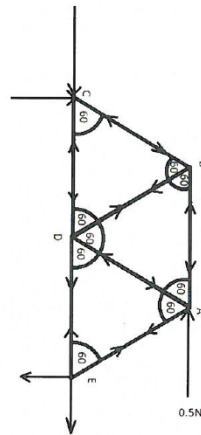


Figure 16

Due to there being too many assumptions and unknowns the reaction forces were obtained using simulation software. They could have been calculated by hand, but this would have eaten up excess time and was out with the scope of the project. The reaction forces are shown in Figure 17.

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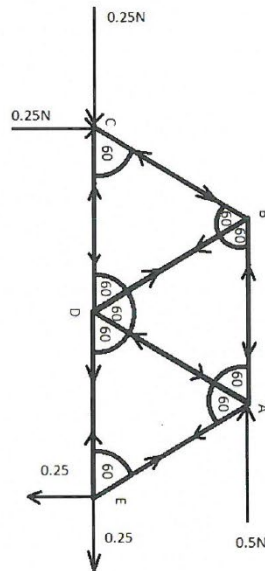


Figure 17

It was then necessary to calculate the forces within each of the members to make sure the material could withstand it.

Node E

$$\sum F_{up} = \sum F_{down}$$

$$F_{DE} + F_{AE} \sin(30) = 0.25$$

$$\sum F_{left} = \sum F_{right}$$

$$0.25 = F_{AE} \cos(30)$$

$$F_{AE} = \frac{0.25}{\cos(30)}$$

$$F_{AE} = \frac{\sqrt{3}}{6} N$$

$$F_{DE} + \frac{\sqrt{3}}{6} \sin(30) = 0.25$$

$$F_{DE} = 0.5 - \frac{\sqrt{3}}{6} \sin(30)$$

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$$F_{DE} = \frac{3 - \sqrt{3}}{12} N$$

Node A

$$\sum F_{up} = \sum F_{down}$$

$$0.5 = F_{AB} + F_{AD} \sin(30) + \frac{\sqrt{3}}{6} \sin(30)$$

$$F_{AB} + F_{AD} \sin(30) = 0.5 - \frac{\sqrt{3}}{6} \sin(30)$$

$$\sum F_{left} = \sum F_{right}$$

$$F_{AE} \cos(30) = F_{AD} \cos(30)$$

$$\frac{\sqrt{3}}{6} \cos(30) = F_{AD} \cos(30)$$

$$F_{AD} = \frac{\sqrt{3}}{6} N$$

$$F_{AB} + F_{AD} \sin(30) = 0.5 - \frac{\sqrt{3}}{6} \sin(30)$$

$$F_{AB} + \frac{\sqrt{3}}{6} \sin(30) = 0.5 - \frac{\sqrt{3}}{6} \sin(30)$$

$$F_{AB} = 0.5 - \frac{\sqrt{3}}{6} \sin(30) - \frac{\sqrt{3}}{6} \sin(30)$$

$$F_{AB} = \frac{3 - \sqrt{3}}{6} N$$

Node D

$$\sum F_{up} = \sum F_{down}$$

$$F_{CD} + \frac{\sqrt{3}}{6} \sin(30) + F_{BD} \sin(30) = \frac{3 - \sqrt{3}}{12}$$

$$F_{CD} + F_{BD} \sin(30) = \frac{3 - \sqrt{3}}{12} - \frac{\sqrt{3}}{12}$$

$$F_{CD} + F_{BD} \sin(30) = \frac{3 - 2\sqrt{3}}{12}$$

$$\sum F_{left} = \sum F_{right}$$

$$\frac{\sqrt{3}}{6} \cos(30) = F_{BD} \cos(30)$$

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$$F_{BD} = \frac{\sqrt{3}}{6} N$$

$$F_{CD} + F_{BD} \sin(30) = \frac{3-2\sqrt{3}}{12}$$

$$F_{CD} + \frac{\sqrt{3}}{6} \sin(30) = \frac{3-2\sqrt{3}}{12}$$

$$F_{CD} = \frac{3-2\sqrt{3}}{12} - \frac{\sqrt{3}}{6} \sin(30)$$

$$F_{CD} = \frac{3-2\sqrt{3}}{12} - \frac{\sqrt{3}}{12}$$

$$F_{CD} = \frac{3-3\sqrt{3}}{12}$$

$$F_{CD} = \frac{3(1-\sqrt{3})}{12}$$

$$F_{CD} = \frac{1-\sqrt{3}}{4} N$$

Node B

$$\sum F_{left} = \sum F_{right}$$

$$\frac{\sqrt{3}}{6} \cos(30) = F_{BC} \cos(30)$$

$$F_{BC} = \frac{\sqrt{3}}{6} N$$

We can now bring together all the calculated forces in the members.

$$F_{AE} = \frac{\sqrt{3}}{6} N \approx 0.29N$$

$$F_{DE} = \frac{3-\sqrt{3}}{12} N \approx 0.11N$$

$$F_{AD} = \frac{\sqrt{3}}{6} N \approx 0.29N$$

$$F_{AB} = \frac{3-\sqrt{3}}{6} N \approx 0.21N$$

$$F_{BD} = \frac{\sqrt{3}}{6} N \approx 0.29N$$

$$F_{CD} = \frac{1-\sqrt{3}}{4} N \approx -0.18N$$

$$F_{BC} = \frac{\sqrt{3}}{6} N \approx 0.29N$$

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We can see from the calculated forces in the members that 0.29N is the greatest force experienced by any of the members. The internal support structure, as discussed in the research section will be 3D printed with each member having dimensions of 1x12mm we can therefore use the stress equations to find out if these dimensions are adequate.

$$\sigma = \frac{F}{A}$$

$$\sigma = \frac{0.29}{12}$$

$$\sigma = 0.024Nmm^{-2}$$

The paper "Mechanical Properties of 3D-Printing Polylactic Acid Parts subjected to Bending Stress and Fatigue Testing" states that the yield stress of PLA is 60MPa (Travieso-Rodriguez, et al., 2019). 1MPa is equivalent to  $1Nmm^{-2}$  therefore we can see that the member can easily withstand the required forces.

#### Structural Modelling of Subsystem 2: Main Hull.

The aims of this project state that ROV must be able to withstand a depth of up to 50m. It was calculated in Equation 1 that this equates to a pressure of about 5 atmospheres or  $0.502Nmm^{-2}$ . Barlow's formula was used to calculate the buckling pressure of the main body section for different thicknesses of PVC pipe (as it was decided in the research section that the main body section should be constructed from PVC). Barlow's formula is usually used to calculate maximum internal pressure that a pipe can withstand however in this case the pressure will be external. To account for the external pressure the maximum compressive stress of PVC will be used as opposed to the maximum tensile stress.

$$P = \frac{2\sigma_{\theta}S}{D}$$

Equation 15 (Barlow's formula)

Initially standard 127mm outside diameter PVC pipe was modelled. The wall thickness was taken as 1mm as this is what the sellers for this type of pipe quoted. The maximum compressive stress of PVC was taken as 4000psi or  $\approx 27.58Nmm^{-2}$  (Dodge, 2010).

$$P = \frac{2 \times 27.58 \times 1}{127}$$

$$P = 0.43Nmm^{-2}$$

$$P = 0.43Nmm^{-2} < 0.502Nmm^{-2}$$

Equation 16

As shown by the above equation the maximum pressure that this type of PVC tube could withstand is less than the required pressure. This means that if this type of PVC pipe were to be used then the hull would fail, destroying the ROV at slightly less than half the required depth. Another type of PVC pipe was therefore modelled this time with a diameter of 125mm and a wall thickness of 7.5mm as quoted by the manufacturer (Wickes, 2021).

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$$P = \frac{2 \times 27.58 \times 7.5}{125}$$

$$P = 3.3 \text{Nmm}^{-2}$$

$$P = 3.3 \text{Nmm}^{-2} > 0.502 \text{Nmm}^{-2}$$

Equation 17

We can see from this calculation that PVC pipe of these dimensions can easily withstand the required pressure. A calculation was performed to determine the factor of safety of this PVC pipe.

$$\text{Factor of safety} = \frac{\text{ultimate stress}}{\text{safe working stress}}$$

$$\text{Factor of safety} = \frac{3.3 \text{Nmm}^{-2}}{0.502 \text{Nmm}^{-2}}$$

$$\text{Factor of safety} = 6.6 \text{ (1dp)}$$

$$\approx 7$$

This is quite a high factor of safety especially considering that there is no real threat to life, were the ROV to fail. On the other hand though, one of the goals of this project is to reduce cost and this includes operating and maintenance costs, so if the ROV is less likely to fail and is more reliable then you will not have to pay for repairs and it will last a while. This I think outweighs the slightly higher initial cost of obtaining PVC pipe with a slightly higher than required strength.

The maximum deflection of the main body tube due to pressure can also be calculated. In this case we are calculating the maximum radial deflection ( $\Delta r$ ) in millimetres. The formula for calculating the maximum radial deflection of cylindrical pressure vessel closed at both ends and under external pressure is shown below.

$$\Delta r = \frac{-P_o r_o^2 r}{E(r_o^2 - r_i^2)} \left[ (1 - \nu) + (1 + \nu) \frac{r_i^2}{r^2} \right]$$

$P_o$ : External Pressure

$r_o$ : external radius

$r$ : radius to point of interest

$E$ : young's modulus

$r_i$ : internal radius

$\nu$ : Poisson's ratio

Equation 18 (StructX, 2024).

Poisson's ratio for PVC is taken as 0.38 (Floral & Peters, 1996) and the young's modulus of PVC was taken as  $3.7 \times 10^3 \text{Nmm}^{-2}$  (Escudier & Atkins, 2019). We can then substitute in the appropriate values and the maximum radial deflection can be calculated.

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$$\Delta r = \frac{-0.502 \times 125^2 \times 117.5}{3.7 \times 10^3 (125^2 - 110^2)} \left[ (1 - 0.38) + (1 + 0.38) \frac{110^2}{117.5^2} \right]$$

We can now simplify this equation and solve for  $\Delta r$  to get the maximum radial deflection.

$$\Delta r = -0.13 \text{ mm (2 d.p.)}$$

We can see from the answer to the equation that the maximum radial deflection is 0.13mm which is a negligible value so is not of any concern when designing the structure.

### Structural Modelling of Subsystem 3: Buoyancy system

As discussed in the research section conventionally most of the ROVs buoyancy comes from its pressure vessel (Fengyukun, 2003). It is important to know the force of this buoyancy so we can calculate how much ballast is required to achieve neutral buoyancy. An approximation of the main hull shape (as decided in the research section) is shown below. This approximation will be used to calculate volume and therefore buoyancy. It consists of a hemisphere, a cylinder, and a quadratic curve.

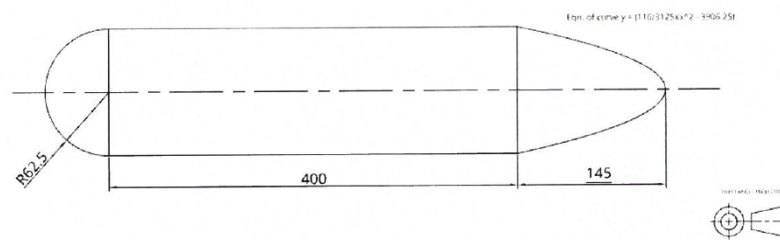


Figure 18

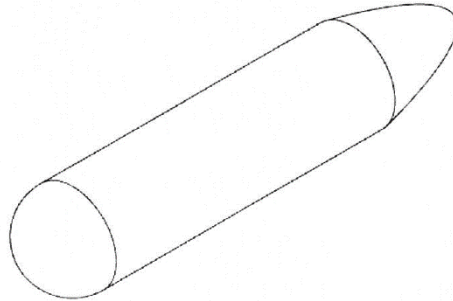


Figure 19

The equations to calculate the volume of a hemisphere and cylinder are shown below.

$$\text{Volume of a cylinder: } V = \pi r^2 h$$

$$\text{Volume of a sphere: } V = \frac{4}{3} \pi r^3$$

The equation of the quadratic curve with roots at  $\pm 62.5$  and a turning point at  $-145$  is derived below. We can then take the integral of this equation and revolve it round the axis to find the volume of the stern section.

$$y = (x + 62.5)(x - 62.5)$$

$$y = x^2 - 3906.25$$

We can then take the derivative to find the x coordinate of the turning point.

$$\text{t. p. when } \frac{dy}{dx} = 0$$

$$\frac{dy}{dx} = 2x$$

$$2x = 0$$

$$x = 0$$

We can see from these equations that the turning point is at  $x = 0$ . We can therefore then substitute in the y value of the turning point at  $x = 0$  to get the equation of the curve.

$$y = \frac{1}{p}(x^2 - 3906.25)$$

$$-145 = \frac{1}{p}((0)^2 - 3906.25)$$

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$$\begin{aligned}
 -145 &= -\frac{3906.25}{p} \\
 p &= \frac{-3906.25}{-145} \\
 p &= \frac{3906.25}{145} \\
 \frac{1}{p} &= \frac{145}{3906.25} \\
 \frac{1}{p} &= \frac{116}{3125} \\
 y &= \frac{116}{3125}(x^2 - 3906.25)
 \end{aligned}$$

We can then integrate and revolve to find volume.

$$\begin{aligned}
 \text{Volume} &= \pi \int_a^b x^2 dy \\
 3125y &= 116(x^2 - 3906.25) \\
 \frac{3125}{116}y &= x^2 - 3906.25 \\
 x^2 &= \frac{3125y}{116} + 3906.25 \\
 \text{Volume} &= \pi \int_a^b \left(\frac{3125y}{116} + 3906.25\right) dy \\
 V &= \pi \int_{-145}^0 \left(\frac{3125y}{116} + 3906.25\right) dy \\
 V &= \pi \left[\frac{3125y^2}{116(2)} + 3906.25y\right]_{-145}^0 \\
 V &= \pi \left[\frac{3125y^2}{232} + 3906.25y\right]_{-145}^0 \\
 V &= \pi \left(\frac{3125(0)^2}{232} + 3906.25(0)\right) - \left(\frac{3125(-145)^2}{232} + 3906.25(-145)\right) \\
 \text{Volume} &= 889708.857\text{mm}^3
 \end{aligned}$$

We can sub in the appropriate values into the equations for the volume of a cylinder to get the volume of the mid section.

$$\text{Volume of a cylinder: } V = \pi r^2 h$$

$$V = \pi(62.5)^2 400$$

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$$V = 4908738.521\text{mm}^3$$

We can rearrange the equation of the volume of a sphere to get the equation of the volume of a cone and substitute in the appropriate values to get the volume of the front section.

$$\text{Volume of a sphere: } V = \frac{4}{3}\pi r^3$$

$$\text{Volume of a hemisphere} = \frac{1}{2} \frac{4}{3}\pi r^3$$

$$\text{Volume of a hemisphere} = \frac{4}{6}\pi r^3$$

$$\text{Volume of a hemisphere} = \frac{2}{3}\pi r^3$$

$$V = \frac{2}{3}\pi(62.5)^3$$

$$V = 511326.9293\text{mm}^3$$

We can then add together the values of volume calculated for each of the sections to get the total approximate volume of the ROV.

$$V = 511326.9293 + 4908738.521 + 889708.857$$

$$V = 6309774.307\text{mm}^3$$

$$V = 0.0063\text{m}^3$$

The equation for the force of buoyancy is shown below.

$$F_b = -\rho g V_f$$

$F_b$ : Buoyant force

$\rho$ : Fluid density

$g$ : Acceleration due to gravity

$V_f$ : Volume of fluid displaced

We now substitute in the appropriate values to get the buoyant force experienced by the ROV.

$$F_b = -(997)(-9.8)(0.0063)$$

$$F_b = 61.6\text{N (1dp)}$$

We can then use the equation for the force of weight to calculate the ballast needed to achieve neutral buoyancy.

$$F = mg$$

$$m = \frac{F}{g}$$

$$m = \left| \frac{61.6}{-9.8} \right|$$

$$m = 6.3\text{kg}$$

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We can see from the above equations that to achieve neutral buoyancy the ROV would require roughly 6.3kg of ballast.

#### Electrical Modelling of Subsystem 4: Control system.

It is necessary to allow some adjustment of the speed of the motors. This can be done using pulse width modulation (PWM). To generate a PWM signal a 555 timer or equivalent can be used. The equations associated with a 555 timer are shown below.

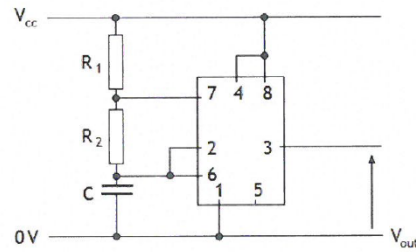


Figure 20 (Scottish Qualifications Authority, 2019).

$$f = \frac{1.44}{(R_1 + 2R_2)C}$$

$$\text{Mark} = 0.7(R_1 + R_2)C$$

$$\text{Space} = 0.7R_2C$$

Equation 19 (Scottish Qualifications Authority, 2019).

It was decided that the upper limit should have a duty cycle of 90%, this represents a mark time of 9ms and a space time of 1ms, and the lower limit should have a duty cycle of 50%, this represents a mark time of 1ms and a space time of 1ms. It was decided that the capacitor should be taken at a value of  $100 \times 10^{-8}C$  for the purposes of calculation, this could be subject to change however depending on how reasonable the calculated resistor values are.

Low Power (50% duty cycle)

$$\text{Space} = 0.7R_2C$$

$$1 \times 10^{-3} = 0.7R_2 \times 100 \times 10^{-8}$$

$$R_2 = \frac{1 \times 10^{-3}}{0.7 \times 100 \times 10^{-8}}$$

$$R_2 = 1428.6\Omega \text{ (1dp)}$$

$$R_2 \approx 1.4k\Omega$$

$$\text{Mark} = 0.7(R_1 + R_2)C$$

$$1 \times 10^{-3} = 0.7(R_1 + 1.4 \times 10^3) \times 100 \times 10^{-8}$$

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$$\frac{1 \times 10^{-3}}{0.7 \times 100 \times 10^{-8}} = R_1 + 1.4 \times 10^3$$

$$\frac{1 \times 10^{-3}}{0.7 \times 100 \times 10^{-8}} - 1.4 \times 10^3 = R_1$$

$$R_1 = 0\Omega$$

High power (90% duty cycle)

$$Mark = 0.7(R_1 + R_2)C$$

$$\frac{9 \times 10^{-3}}{0.7 \times 100 \times 10^{-8}} - 1.4 \times 10^3 = R_1$$

$$R_1 = 11.457k\Omega$$

$$R_1 \approx 11.5k\Omega$$

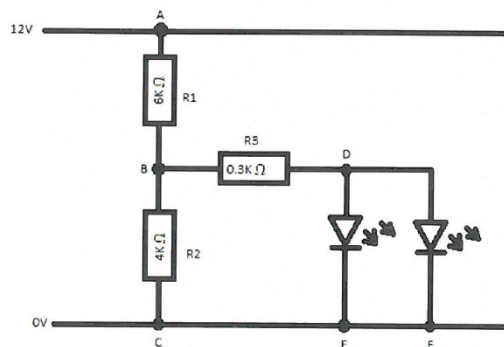
We can therefore see that the required component values to produce the required PWM signals are as follows:

$R_1$ : Variable resistor 0 – 11.5k $\Omega$

$R_2$ : Resistor 1.4k $\Omega$

$C$ : Capacitor  $100 \times 10^{-8}F$  (1 $\mu F$ )

The headlight system of the ROV will include some resistors to regulate voltage and current to the LEDs to ensure they are operating correctly and are not damaged. Nodal analysis can be used to calculate voltages at the nodes of the headlight subsystem circuit. A diagram of this circuit is shown below.



We know that the voltage drop across the LEDs should be 2V therefore we can give node D this value. We can also see that nodes C, E and F would all be at zero volts. Additionally we can also deduce from the diagram that node A would be at 12v. this leaves only node B to be calculated. We can use Kirchhoff's laws to calculate this.

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$$\sum_{i=1}^n I_i = 0$$

$$\sum \frac{V_{inside} - V_{outside}}{R_{inbetween}} = 0$$

$$\frac{V_B - V_A}{R_1} + \frac{V_B - V_D}{R_3} + \frac{V_B - V_C}{R_2} = 0$$

$$\frac{V_B - 12}{6 \times 10^3} + \frac{V_B - 2}{300} + \frac{V_B - 0}{4 \times 10^3} = 0$$

We can then simplify to get our value of voltage at node B ( $V_B$ ).

$$\frac{4 \times 10^3(V_B - 12)}{6 \times 10^3} + \frac{4 \times 10^3(V_B - 2)}{300} + V_B = 0$$

$$\frac{300 \times 4 \times 10^3(V_B - 12)}{6 \times 10^3} + 4 \times 10^3(V_B - 2) + 300V_B = 0$$

$$300 \times 4 \times 10^3(V_B - 12) + 6 \times 10^3 \times 4 \times 10^3(V_B - 2) + 6 \times 10^3 \times 300V_B = 0$$

$$1200 \times 10^3(V_B - 12) + 24 \times 10^6(V_B - 2) + 1800 \times 10^3V_B = 0$$

$$1200 \times 10^3V_B + 24 \times 10^6V_B + 1800 \times 10^3V_B - 14.4 \times 10^6 - 48 \times 10^6 = 0$$

$$1200 \times 10^3V_B + 24 \times 10^6V_B + 1800 \times 10^3V_B = 14.4 \times 10^6 + 48 \times 10^6$$

$$27 \times 10^6V_B = 62.4 \times 10^6$$

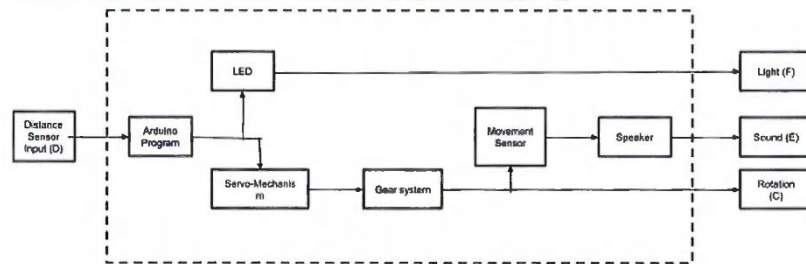
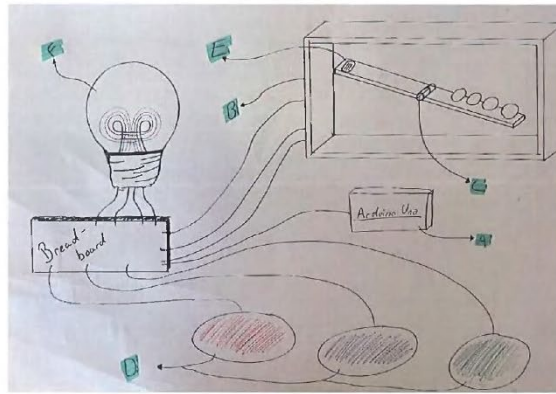
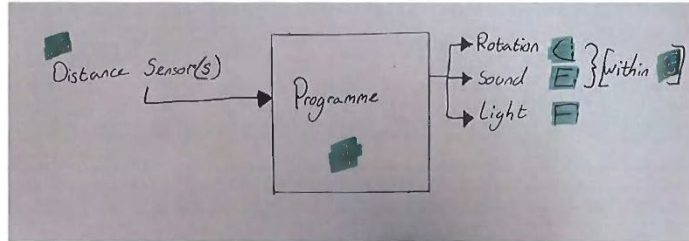
$$V_B = \frac{62.4 \times 10^6}{27 \times 10^6}$$

$$V_B = 2.31V \text{ (2dp)}$$

# Constructing and/or simulating a solution

## Simulation

### Sub-system Diagram



### The Program (A)

To make the process easier, I have broken down the program into manageable chunks to complete one at a time. So firstly, I have written a program to connect the input -

distance sensors (D) - into the program (A) to the output - the LED (F). This was written for Arduino and fulfils specifications 1.1 and 1.3. The code is displayed below with my comments and thought process highlighted:

```
int LED_B = 3;
int LED_G = 5;
int LED_R = 6; //
int blue = A0;
int green = A1;
int red = A2;

// the setup routine runs once when you press reset.
void setup() {
  // initialize serial communication at 9600 bits per second:
  Serial.begin(9600);

  // configure LED pins for the output.
  pinMode(LED_B, OUTPUT);
  pinMode(LED_G, OUTPUT);
  pinMode(LED_R, OUTPUT);
}

// the loop routine runs over and over again forever:
void loop() {
  // reads the input on analog pin A2 (value between 0 and 1023)
  int analogValueR = analogRead(A2);

  // scales it to brightness (value between 0 and 255)
  int brightnessR = map(analogValueR, 0, 1023, 0, 255);

  // sets the brightness LED that connects to pin 6
  analogWrite(LED_R, brightnessR);

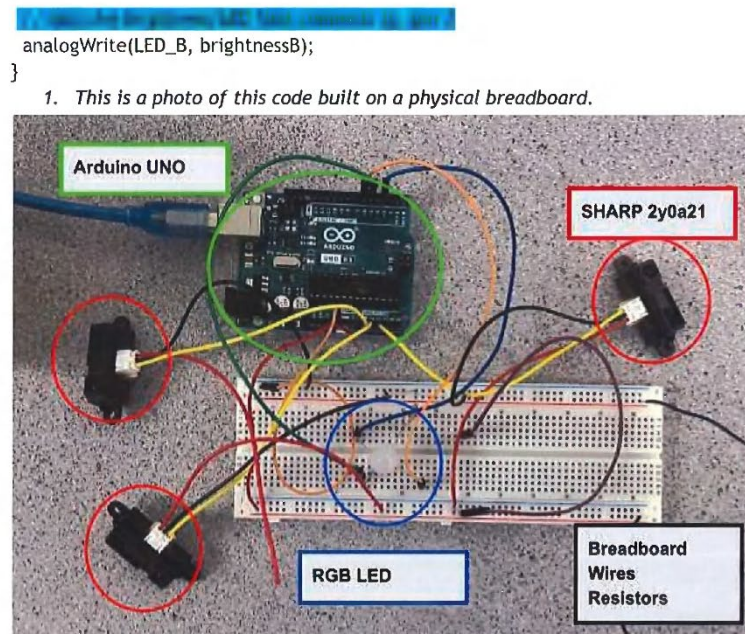
  // reads the input on analog pin A1 (value between 0 and 1023)
  int analogValueG = analogRead(A1);

  // scales it to brightness (value between 0 and 255)
  int brightnessG = map(analogValueG, 0, 1023, 0, 255);

  // sets the brightness LED that connects to pin 5
  analogWrite(LED_G, brightnessG);

  // reads the input on analog pin A0 (value between 0 and 1023)
  int analogValueB = analogRead(A0);

  // scales it to brightness (value between 0 and 255)
  int brightnessB = map(analogValueB, 0, 1023, 0, 255);
```



From my mathematical modelling and finding the relationship between the servo mechanism and the distance sensors, I have written a program for the same Arduino circuit (with servo added). This connects the input - distance sensors (D) - into the program (A) to the output - rotation (C). Here it is written below:

```

void setup() {
  pinMode(trigPin1, OUTPUT); //set trig pin 1 as output
  pinMode(echoPin1, INPUT); //set echo pin 1 as input
  pinMode(trigPin2, OUTPUT); //set trig pin 2 as output
  pinMode(echoPin2, INPUT); //set echo pin 2 as input
  pinMode(trigPin3, OUTPUT); //set trig pin 3 as output
  pinMode(echoPin3, INPUT); //set echo pin 3 as input
  servo.attach(9); //attach servo to pin 9
}

void loop() {
  long duration1, distance1; //variables for first distance sensor
  long duration2, distance2; //variables for second distance sensor
  long duration3, distance3; //variables for third distance sensor
}

```

```

digitalWrite(trigPin1, LOW);
delayMicroseconds(2);
digitalWrite(trigPin1, HIGH);
delayMicroseconds(10);
digitalWrite(trigPin1, LOW);
duration1 = pulseIn(echoPin1, HIGH);
distance1 = duration1 * 0.034 / 2;

//get distance from second sensor
digitalWrite(trigPin2, LOW);
delayMicroseconds(2);
digitalWrite(trigPin2, HIGH);
delayMicroseconds(10);
digitalWrite(trigPin2, LOW);
duration2 = pulseIn(echoPin2, HIGH);
distance2 = duration2 * 0.034 / 2;

//get distance from third sensor
digitalWrite(trigPin3, LOW);
delayMicroseconds(2);
digitalWrite(trigPin3, HIGH);
delayMicroseconds(10);
digitalWrite(trigPin3, LOW);
duration3 = pulseIn(echoPin3, HIGH);
distance3 = duration3 * 0.034 / 2;

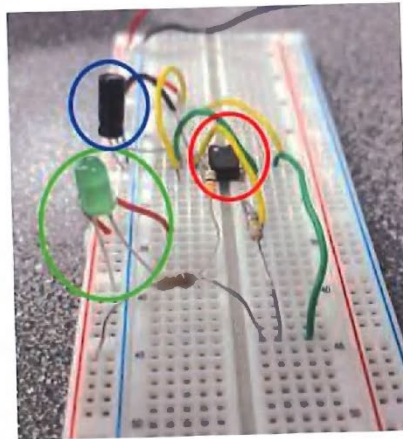
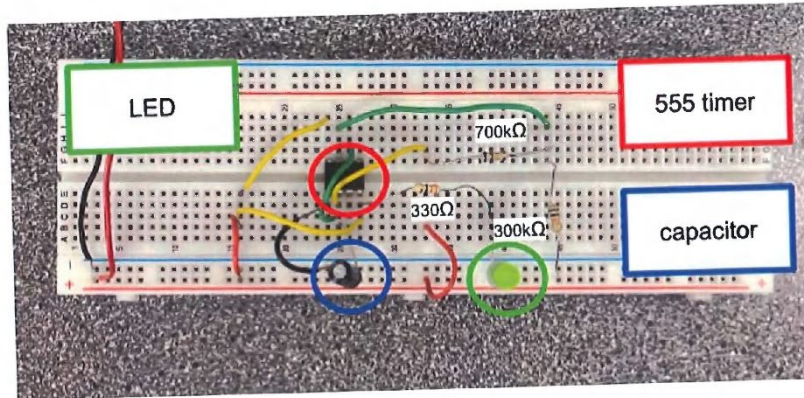
//move servo to 0 degrees if object is too close
if(distance1 < 10){ //if object is less than 10 units away from first sensor
  servo.write(0); //move servo to 0 degrees
}
else if(distance2 < 10){ //if object is less than 10 units away from second sensor
  servo.write(90); //move servo to 22.5 degrees
}
else if(distance3 < 10){ //if object is less than 10 units away from third sensor
  servo.write(180); //move servo to -22.5 degrees
}
else{ //if no object is detected within 10 'units'
  servo.write(90); //move servo to 0 degrees
}

delay(100); //delay for stability
}

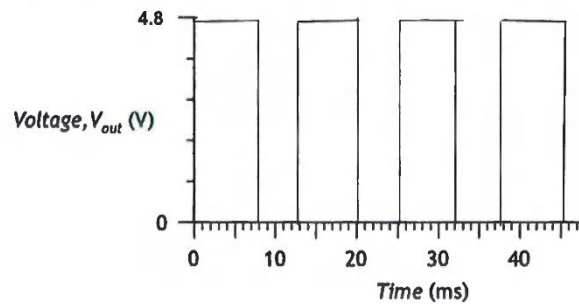
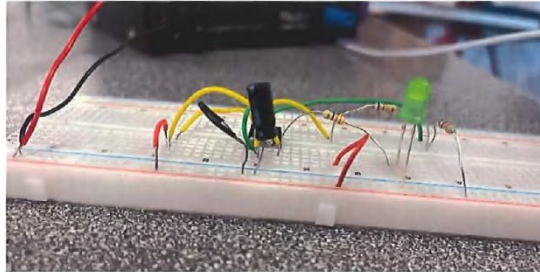
```

Since none of the output/input pins overlap, the two sets of codes are compatible and can easily work together. This would be the base for the whole design and it is the most important part for ensuring it runs smoothly. However, I was unable to make a physical prototype of the breadboard as there were no servo-mechanisms available to me in my school at the time.

### “On Light” 555 timer



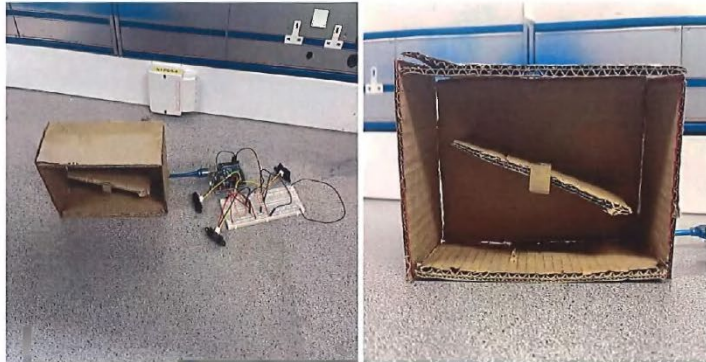
Based on my mathematical modelling (page 17-18) I have created this circuit of the 555 timer using a 700kΩ and 300kΩ resistor. After putting the circuit together, I used a multimeter to measure the voltage and current to ensure there was no voltage loss, of which there was no impact on the circuit. Overall, my calculations were correct and the circuit works well, with the LED turning on for 0.75 second and turning off for 0.5 seconds.



Measured voltage outputs from circuit above.

### The Platform(B) and Rotation(C)

Based on mathematical analysis, I opted to utilise soft plywood as the platform material. This was due to its ability to endure the stresses exerted by the marbles and crank without bending so much that it interfered with the device's operation. *Seen below is a very basic model of the box made out of cardboard 'connected' to the breadboard:*



This is the same breadboard used in simulation diagram 1 (above), connecting distance sensors to the LED.

## Gear system connected to platform

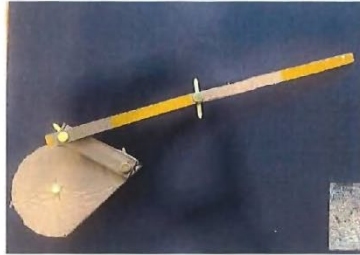


Photo A

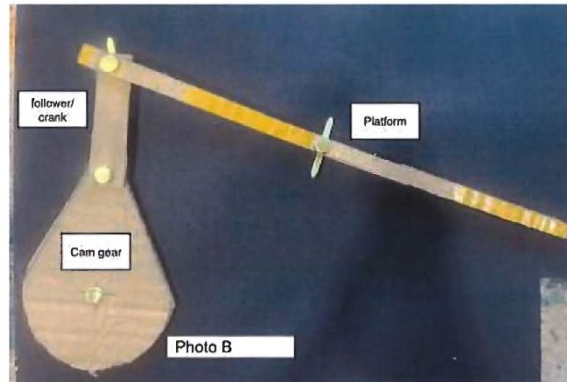


Photo B

To explain how the diagrams would work, the servo motor would be connected to the cam gear, making it rotate. The end of the cam gear would be attached to the follower/crank rod which lifts the platform to oscillation. Since my school did not have actual cam gears on hand and I had a limited time-frame, I used cardboard to imitate the platform's gear system, ensuring that it was cut to size before attaching the sections using a paper fastener. Using a ruler and a protractor, I verified that the platform reaches  $+22.5^\circ$  when the servo is turned anti-clockwise, as shown in Photo B. However, I noticed that when turned the opposite direction (clockwise), the platform rotates too far ( $76^\circ$ ). As a result, I will include a new 'stopper' in the box that prevents the cam from spinning too far.

# Evaluation

## Evaluation

Have the specifications been met?

Specification	Has it been met?
1.1	Yes
1.2	Yes
1.3	Yes
2.1	Yes
2.2	Yes
2.3	Yes
3.1	No
3.2	Yes
3.3	No
3.4	No
3.5	Yes
4.1	Yes
4.2	Yes
4.3	Yes
4.4	No
4.5	Yes
4.6	No
4.7	Yes

### Specifications that have been met

Each one of the structure specifications (1.1-1.3) have been met. This has been proven through the mathematical modelling demonstrated above with e.g, the maximum bending moment being less than 400 Nm. The same is applicable to all of the motor specifications as through simulation it is shown that the nodal analysis can change the input voltage that the motor could have applied to it. This could be further developed to include a variable resistor to more accurately show this concept. However such an analysis would need to be further worked on separately.

### Specifications that have not been met.

3.1, 3.3 and 3.4: For these specifications I had not set aside enough time to undertake analysis and complete them as hoped. This is primarily because my research and mathematical modelling for the rest of the system took a lot longer than expected. If I was doing this project again I would allow for even more time to better analyse each model. With time constraints I was not able to model or investigate the implementation of a speed sensor. However, as the rest of the electronics and coding had been modelled via circuits or flowcharts, I took the decision to continue working through that workload and to support the results for these using the simulations outlined above.

4.4: This task was included to make the climbing experience more realistic and to increase the intensity of the climb (make it harder). However as the time allotted to each stage of the analysis and simulation process was gradually increased, the time to look more closely at this aspect of the project was decreased and in the end this task became challenging to investigate credibly with what time remained. That said, this part of the system is still needed in the plan because it could easily be used as a future development to this project.

4.6: The maximum deflection has not been calculated for a few reasons. Firstly, for the parameters analysed, the maximum calculated bending stress on the beam is  $0.1Nm^{-2}$  with a Young's modulus of  $1.0976Knm^{-2}$ . The Young's modulus value is more than 100 times larger than what was calculated in the designed system. This value shows that there will be an incredibly minute value of deflection if any deflection in the beam when it is made of stainless steel with the dimension of my design. The two values combined imply that it would need a large amount of excess force applied to the system for any bending to occur. Moreover the values support a conclusion that the beam as designed is capable of withstanding similar forces even at an extreme deflection.

### Evaluation of the Process

When I started this process I had not fully appreciated the magnitude of work needed to support this project and the amount of hours I would need to invest in research, mathematical modelling and simulation. However, I have been able to work efficiently on the parts of the project that I have undertaken and I updated the Gantt charts to cover the workloads completed and still needed to be done as soon as I better understood the project timetable and deliverable schedule. Again, my system research and mathematical modelling took longer than I thought it would, which shows that this type of preparation work can often require a lot more time set aside for it. This gave me less time to model and simulate each part of the system and also meant that I could not move on to Create Phases, or Testing Phases either. Nevertheless, the project as completed to the level so far has proved useful and insightful and has laid the groundwork for possible further development in the future.

### Further investigation

If this project was to be continued, the next steps would include: simulation of coding, construction and building of the climbing treadmill structure, testing of the construction, and finally researching and developing the ability for the wall to change angle. These would allow for the wall to move further towards completion and for the project to be constructed, tested and used. Such additional project phases would prove that the initial concept and ideas shown throughout this project supported a usable and effective solution for climbers to find a credible way to train for their chosen sport whilst still being small enough to use in a house. Separately, as my design includes a 2.4m wide climbing surface - this might be unrealistic to deliver - so it would be useful to investigate the forces applied to a more compact wall (similar to the 1.2-1.4m systems already in the marketplace).

### Overall Evaluation of the Process:

To evaluate this process as a whole there are a few factors that affected the project, this being: original plan, execution of the plan and time management.

### Original Plan

To start with this plan was incredibly ambitious, there were many potentially complicated problems to solve and a lot of precise mathematical calculations and complex simulations that would need to be further analysed before any final product was to be made. On top of that it is a large product and so making a full sized version would be difficult in a school design situation. This said, I began this process confident in my ability to complete the project, if not all of it - then at least the most important parts, which I have shown I can do. This has required a lot of research into each subsystem. As I got further into the process I was able to build up the skills and resources needed to effectively show my ideas, design working models, and to understand and define the designs of some of the major subsystems.

### Execution of the plan

It is clear to see that the plan has changed significantly since the start of the process. This is because there was a need to change the schedule to incorporate more time to better evaluate specific key subsystems through mathematical modelling and simulation, and to have a near finished result for this analysis towards the end of this project. I am happy that each component that is designed can effectively be implemented and that, in the future, a working model incorporating the work included in this analysis can be delivered (and that a full scale wall can eventually be constructed).

### Time Management

I managed my time well through this project. However with other commitments at school it was very difficult to support the continuous workload that this project demanded, and particularly so when some stages of the project began to take much more time than originally planned. The changes to analysis, research and system modelling was acknowledged and the plan was updated to accommodate these changes. This allowed me to work effectively on the part of the design that needed to be focused on with what time was remaining. Overall the execution of this project has been effective as I have designed, modelled, and credibly simulated the largest and most crucial subsystems in the proposed climbing treadmill design.