Candidate 1 evidence

Outline

Project Aims

The aim of this project is to create a calming product for a sensory room for special needs children in a nursery or a primary school. The given timescale is twelve weeks to develop, design and build.

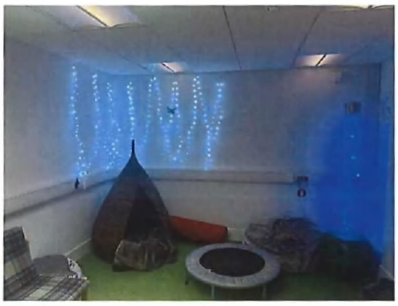
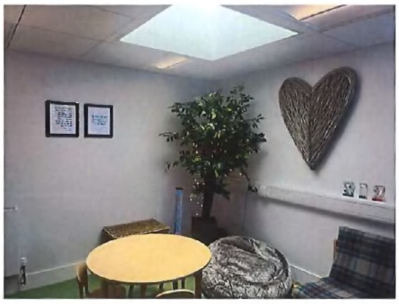
I had this idea of creating a device for a children's sensory room based on my own experience having an autism diagnosis and personally utilising technology to deal with overwhelming surroundings. The key points of the project with calming lighting, sounds and some simple movement came from a mixture of my visit to the primary school sensory room and research. The NHS provides advice on simple ways to help autistic children.

These include:

- letting your child wear headphones to listen to calming music
- turning down or removing bright lights
- distraction techniques, such as fiddle toys
- planning ahead for any change in routine, such as a different route to school

(2022) *NHS choices*. Available at: https://www.nhs.uk/conditions/autism/autism-and-everyday-life/help-with-behaviour/ (Accessed: 12 March 2024).

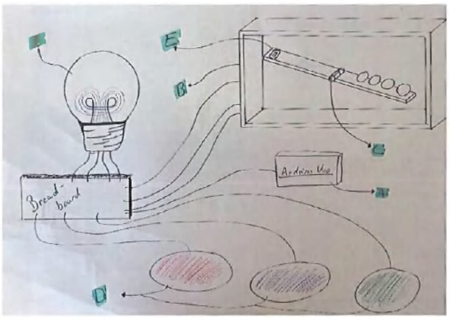
As a part of the research, I visited my old primary school's sensory/nurture room. During this visit, I did some exploration on what generally calms children when they have been overstimulated or have sensory issues. From my open questions to the children who use the room I have confirmed that they generally prefer interactive devices and soft lighting and dislike loud and sudden noises. I will work this into my specifications and make sure to go back when my project is finished so I can get some more feedback and understand if there is anything I could do better.

Basic Specifications

- Device's LED must change colour depending on the signal from the distance sensors.
- Device's Platform's angle of rotation must change depending on the signal from the distance sensors.
- Device's Platform must be able to withstand the weight of four marbles moving across each side.
- Device must be easy to understand and easy to use.
- Device's distance sensor must be able to recognise the 95th percentile of children's hand sizes.
- Device must have soft lighting
- Device must emit calming noises

This photo is a very basic drawing of how the device will work:



A - Programme
B - Box
C - Rotation
D - Distance Sensor
E - Sound
F - Light

Key Resources

- Arduino Uno R3
- distance sensor x 3
- Some kind of motor that connects electrical input to mechanical movement output
- Wires
- Resistor
- Box...?
- Speaker
- Marbles x 4
- Levers or rotor?
- Some kind of platform
  - must be sturdy and thick enough to withstand movement but lightweight enough to be moved.
- Breadboard

Scheduling

Firstly, I need to connect the Servo to a gear system that will result in the rotation of the platform. As part of this I need to match the output of the Servo Mechanism to the rotation of the platform. This means that I can write the programme according to the outputs. This will take approximately three weeks although I am giving myself a leeway of another week just as a precaution.

Secondly, I will spend around five weeks on my programme. This is because I will have to work on other segments of the project at the same time to make sure that everything works together. I am also giving myself the leeway of another week to work on the programme as it is the most important part of my project. I feel it is important to give some extra contingency as when this is done it will be a key milestone in my project.

For the other segments, I aim for the box to be finished by the seventh week, the LED to be finished by the seventh week, the distance sensors to be connected by the eighth week and the speakers to be working around the tenth week.

I used my timeline to form a Gantt chart to plan my time for the weeks of my project.

Gantt Chart

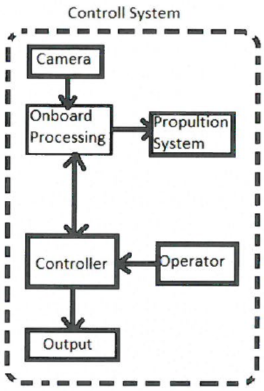
part\week	1	2	3	4	5	6	7	8	9	10	11	12
A				A	A	A	A	A	a			
				S	S	S	S	S				
B					B	B	B					
					R	S	S/B					
C	C	C	C	c								
	R	MM	S/B									
D						D	D	d				
						S	S					
E							E	E	E	e		
							R	S	S			
F						F	f					
						S						

A - Programme
B - Box
C - Rotation
D - Distance Sensor
E - Sound
F - Light

R - research
MM- mathematical modelling
S - simulate
B - build

Research, analysis and specification

Initial Subsystem Diagram.



Analysis of problem.

The problem of designing a low-cost solution for underwater visual surveillance requires some form of remotely operated underwater device to be designed. It can be argued that an ROV is the best solution to the problem as opposed to an alternative such as an underwater camera system for divers because an ROV provides the capability to access more difficult environments as well as potentially requiring less expertise to use compared to training or hiring a diver. This helps to meet the initial aim of broadening accessibility. All the sub systems of an ROV must be considered so that research can be planned. The book "*The ROV Manual: A User Guide for Observation Class Remotely Operated Vehicles*" provides some insight on typical ROV subsystems "The frame of the ROV provides a firm platform for mounting, or attaching, the necessary mechanical, electrical, and propulsion components. This includes special tooling/instruments such as sonar, cameras, lighting, manipulator, scientific sensor, and sampling equipment." (Christ & Wernli, 2007) . Since a design goal is to create the device for a low as possible cost and for visual surveillance some of these subsystems can be disregarded, for example as the aim of the project is to provide visual surveillance manipulator and sampling equipment will not be required. However, the ROV will need some form of camera system to provide the visual surveillance capability as well as a control system to relay these signals back to the operator and interpret commands coming from the operator to the ROV. The ROV will also need some way of manoeuvring itself so that it can inspect the desired areas for this it will need propulsion and depth control systems or as the above extract puts it "propulsion components". The previously mentioned control system will get input from the operator and interpret it and relay appropriate signals onward to the depth control and propulsion subsystems so that the ROV can be moved. Of course, as mentioned in the above extract there must be some form of chassis or frame to hold the control, depth, and propulsion systems this will form the main shape of the ROV and provide rigidity and protection to the other systems from water damage and pressure. The chassis must be made of an appropriate material in order to do this though so research will have to be carried out in this area. Different parts of the ROV chassis may require different materials depending on what its function is for example a part holding a motor may be made of metal while the housing for the control system may be made of plastic. Many of the systems will require waterproofing for example motors used in the depth control and propulsion subsystems as well as all the sensitive electronics used in the control system. Therefore, the waterproofing will require some careful research and consideration.

Research strategy.

A major part of the vehicle is the body or chassis, this is what will hold it together and provide protection to the electronics and other systems. It is important that the design of the main body is strong, efficient, and easily produced. To achieve this, I will have to do research on what makes a design hydrodynamic, resistant to pressure and easily manufactured. to meet the design goal of producing a submersible for a low as possible cost, I will need to find and evaluate existing designs in terms of how easily it could be manufactured therefore reducing cost as well as evaluating them on how suitable they are for the chosen application of visual surveying. Once I have concluded, I will produce a body design based on my research. I will gather this information from online resources such as OpenROV (2022) and Homebuiltrovs (2022). I will also gather information from published academic papers such as "Pressure Hull Design Methods for Unmanned Underwater Vehicles" (Meschini, et al., 2019) and "Concepts in submarine shape design" (Moonesun, et al., 2016).

Construction materials are an important element to consider when designing something. In this case the materials used in the construction of the ROV have the potential to greatly affect the overall cost of the project as well as operating limitations. As one of the main goals this project is aiming for is to reduce the cost of such devices this area will require research to be done to make the best decisions on materials. The things I aim to find out about the materials are cost effectiveness, suitability for underwater use, sustainability, how easily they can be worked and efficiency to withstand required forces. Once again will be using online resources to gather information from these will include sites such as Homebuiltrovs (2022) again or Seamor Marine (2024) I will also make use of information from relevant published papers such as "Conceptual design of a composite pressure hull" (Craven, et al., 2016) and "Advanced Materials and their Influence on the Structural Design of AUVs" (Stevenson & Graham, 2003). In this case I will also make use of mathematical analysis to assess materials, for example using Barlow's formula ($P = \frac{2\sigma\theta s}{D}$) to calculate required wall thicknesses (therefore how much is required affecting cost) of different materials.

Some form of propulsion is necessary to provide control and manoeuvrability to the ROV. There are many potential alternatives for propulsion, all with their own pros and cons in this context. It is important to this project that the propulsion system is not overly complex or expensive to obtain or construct as this would be out with the original goal of reducing the cost of underwater surveillance ROVs. Other important things to consider include how suitable the propulsion system is for underwater use or if it could be adapted or modified to work and if so how and how power efficient they are. I must also consider how the propulsion system could be implemented and if this would increase the complexity or cost. Information will be found on the internet using resources such as Homebuiltrovs (2022) and "How to make a water resistant motor housing" Autodesk Instructables (2016) and published articles like "OpenFish: Biometric design of a soft robotic fish for high speed locomotion" (Sander, et al., 2022) and "*Feasibility study of jet propulsion for remote operated underwater vehicles.*" (Gangadharan, 1986) I will also test the performance and suitability of different designs experimentally. For example, testing types of motors submerged and recording how long they run or even if they run at all.

The submersible must have some way of controlling depth, for this we need a variable buoyancy system. As one of the goals of this project is to reduce costs as with the other subsystems it is important that it is suitable for the application and practical to implement thus reducing complexity and price. I will have to gather information on alternative methods of implementing a variable buoyancy system and evaluate them based on the metrics previously mentioned. Like with the other subsystems the information will be gathered from internet sources such as websites and forums, some examples include Blue Robotics' Depth control ideas forum (2014) and "Buoyancy Control of ROVs" (Gill, 2002). I will also gather information from scholarly papers such as "Dynamic buoyancy control of an ROV using a variable ballast tank" (Wasserman, et al., 2003) and "Experimental Study of a Variable buoyancy system for low depth operation." (Sharma, et al., 2023) I will also make use of mathematical analysis to evaluate solutions and come up with a final design, for example I will have to use equations to do with buoyancy and volume ($Fb = \rho V g$) to work out the volumes and masses required to achieve a certain force of buoyancy (Fb).

The ROV needs a system for the operator to be able to control it and for it to be able to process and carry out commands it also needs to be able to gather and send output such as a video signal back to the operator, for this it needs a control system. This may involve analogue electronics and microcontrollers. There are many things to consider when researching and designing the control system for example how are instructions going to get from the operator to the ROV, how are all its systems going to be powered, how is it going to tell the propulsion what to do, how will the camera system work as providing underwater surveillance capabilities was one of the main design goals and how the variable buoyancy system will be controlled. Of course, much of this will have to be researched and designed in accordance with the outcomes and design decisions of the other subsystems so will likely be one of the later tasks. To stick with the design goal of reducing cost I also want to design a control system that makes use of readily available, preferably off the shelf nonspecialized electronics. I will use online resources such as "Controlling an underwater ROV via tether" (Arduino, 2010) and the "Control Systems and Tethers " forum board (Homebuiltrovs, 2023) along with the use of electronics documentation and tutorials. I will also take into account research gathered from published papers such as "A Survey of Underwater Wireless Communication Technologies" (Gussen, et al., 2016).

Many of the ROV's systems will require waterproofing to function correctly and not get damaged, for example any electronics involved in the control systems mentioned in the previous paragraph. The design goal of creating an inexpensive ROV not only covers initial direct costs such as materials but also continued operation and maintenance costs, therefore it is important that critical sensitive components are protected from damage and corrosion caused by seawater which would be expensive to have to continuously fix. For this reason, an effective method of waterproofing all relevant systems must be found or developed. I will have to find ways to waterproof joints between different parts of the ROV as well as finding ways to waterproof any through holes such as ports for cables/ tethers and control rods. Once again to find the information I require I will use online resources such as "Page on possible waterproofing systems for ROVs" (Wikidot, 1997) and "DIY Your ROV- Brief Discussion on Waterproof Tube" (rovmaker, 2022). I will also gather information from published papers such as "Analysis of bonded joints for small craft and marine applications" (Armeanu, 2010).

Research notes analysis and conclusions.

After conducting some research my thoughts on the subject of the chassis are as follows; the front should be a hemispherical dome shape. In terms of pressure resistance, a hemispherical dome shape is the optimal geometry, the paper "Pressure Hull Design Methods for Unmanned Underwater Vehicles" states that a hemispherical dome has a better buckling resistance than other kinds of domes (hemi-ellipsoidal prolate and hemi-ellipsoidal oblate) by about a factor of ten and is advantageous over other geometries such as flat surfaces because stress is more evenly distributed or as the paper puts it "the more commonly used geometry is spherical rather than a flat surface because the distribution of stress on the surface is homogeneous" (Meschini, et al., 2019). The claim that a dome is more resistant to pressure is also backed up by HomebuiltROVs which states "a dome will also handle the pressure better" (Homebuiltrovs, 2022). Additionally, a dome shaped front also offers advantages when it comes to hydrodynamics, the paper "Concepts in submarine shape design" investigates the hydrodynamic properties of different hull shapes. Their results are shown in figure 1, the paper concludes that "the model 6, has the least resistance coefficient that shows the best design for the hull shape" (Moonesun, et al., 2016). We can see from this result that model 6 has a roughly hemispherical front and a rounded, tapered stern. We can also see that this shape also hydrodynamically outperforms other potential shapes that could have been used such as a flat or cone shaped front. This conclusion that a hemispherical front is hydrodynamically efficient is also backed up by information gathered from the HomebuiltROVs forum which states "A dome has better hydrodynamics and less drag" (Homebuiltrovs, 2022). A hemispherical front also offers a greater field of view for the camera system which will be placed in it, of course it will have to be constructed out of a clear material to allow a view out for the camera system. This is also a relatively simple shape so will be easily manufactured or obtained and therefore will be less expensive, meeting the original design goal of reducing cost. A hydrodynamic shape will also increase efficiency and therefore require less power and maintenance also reducing cost.

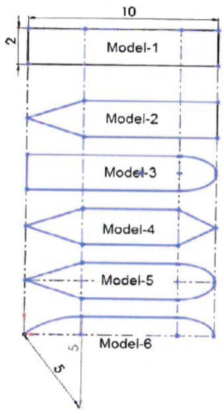


Fig. 2 "Concepts in submarine shape design"

(Moonesun, et al., 2016)

After consideration of the information gathered, I have decided that the best shape for the main mid-section of the hull is cylindrical. The paper "Concepts in submarine shape design" states "Submarines have two major categories for hydrodynamic shape: tear drop shape and cylindrical middle body shape. Tear drop shape has a lot difficulties in construction and cost but has unique advantages in hydrodynamics" (Moonesun, et al., 2016). I have decided to use the cylindrical body type as even though a tear drop shape may provide hydrodynamic advantages the difficulty in construction of such a hull which could withstand the required forces and have the right shape would outweigh the benefits and as one of the main goals of this project is to reduce the cost of ROVs a high complexity and therefore high cost hull shape would be inappropriate. On the other hand, a cylinder is a widely used shape being used in areas such as plumbing, advantages of this include parts already being built to be water and pressure resistant and being cheap and widely available. A cylindrical hull is still relatively hydrodynamic though and resistant to pressure as a paragraph from MITs website puts it while talking about the design of the Atlantis II submersible "As the hull becomes more elongated, its shape becomes almost a cylinder with hemispherical ends and its drag coefficient decreases. But at the same time, as the length of the hull increases frictional drag (another type of drag) increases. Also, the strength due to spherical structure is lost. So, elongation is good, but only to a certain extent" (Massachusetts Institute of Technology , 2005). The paper "Pressure Hull Design Methods for Unmanned Underwater Vehicles" also backs up the claim that a cylindrical hull shape is resistant to pressure "the ideal main structure is usually a cylindrical shell crossed with equidistant rings and end caps" (Meschini, et al., 2019). The system of equations shown below can be used to calculate drag. Optimal dimensions will be calculated later in the mathematical modelling and analysis section.

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

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

C_D: *Coefficient of Drag.*

A_{Proj}: *Projected area of the body as seen from the stream.*

ρ: *Fluid density.*

V: *Free stream velocity.*

F_D: *Force of drag*

R_e: *Reynolds number.*

L: *length.*

μ: *Fluid viscosity.*

Equation 2

(Massachusetts Institute of Technology , 2005)

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

$$C_d = \frac{21.12}{R_e} + \frac{6.3}{\sqrt{Re}} + 0.25, 0.2 < R_e < 2 \times 10^3$$

(Polezhaev & Chircov, 2011)

As for the stern I have decided to use a rounded tapered shape as this is what the "Concepts in submarine shape design" paper concluded was the most hydrodynamically efficient, stating in reference to figure 1 "Bow and stern of submarine should be tapered gradually (by comparison between models 1 and other models). Sharp narrow bow isn't a good selection, but a blunt shape such as an elliptical bow is recommended (by comparison between models 4 and 5)." Although the shape of the stern does have an effect on drag the paper also states "Effects of the bow on the resistance is strongly more than the effect of stern" (Moonesun, et al., 2016). Even though this is the case it is still important to reduce drag and therefore increase efficiency as much as possible. I have therefore concluded that the most optimal hull design for this ROV which maximizes pressure resistance and hydrodynamics while also balancing complexity and cost is one which is comprised of a hemispherical bow followed by a cylindrical midsection and terminated by a tapered and rounded stern. Therse are vastly similar to the conclusions reached by the "Concepts in submarine shape design" paper which states "Curved bow (such as elliptical) and curved stern (such as a sector of circle or parabolic) with cylindrical middle part can be good recommendation for submarines and submersibles" (Moonesun, et al., 2016).

There are a few main candidates for construction materials whose names came up throughout my research. These are: PVC, 3D printed PLA plastic, Anodized Aluminium, Titanium, Stainless Steel, Composites, and ceramics. Starting with ceramics this option was discussed in the paper "Advanced Materials and their Influence on the Structural Design of AUVs" which claims modern high toughness ceramics have been considered as a construction material for pressure hulls since the 1960s although this is the case ceramics have some major drawbacks including high manufacturing costs (which goes against the original design goal of reducing cost) and brittleness (Stevenson & Graham, 2003) on top of this if shattered it would be excessively inconvenient to repair. For these reasons I have decided ceramics would not be an intelligent choice of construction material.

Another potential group of materials is composites this includes materials such as carbon fibre, Kevlar, and fiberglass, as the paper "Conceptual design of a composite pressure hull" puts it "Composites are an attractive material for pressure hulls because of their high strength and low density" going on to say "Submersible pressure hulls manufactured using composites have significant advantages over metallic pressure hulls due to their high stiffness to weight ratio, low density, corrosion resistance and ease of forming into complex shapes" (Craven, et al., 2016). The properties such as high stiffness and ease of forming makes them an extremely attractive option for creating the pressure hull out of, it's not all benefits though composite materials also have some disadvantages which must be considered such as the sustainability and safety of some of the materials used in their construction the paper "Conceptual design of a composite pressure hull" discusses this issue by saying; "The materials themselves, particularly the resin systems, are also toxic, particularly when uncured" (Craven, et al., 2016). This is a fairly major disadvantage on the grounds that these materials if used would be submerged in water potentially close to flora and fauna which could get damaged and poisoned, it goes without saying that this should be avoided. On top of that composite materials are also known to be brittle and undergo sudden and irreversible catastrophic failures of which can be made more likely by the fact that the immersion will tend to cause the laminate to take up water causing degradation over time (Craven, et al., 2016). With all these facts considered composites, while at first may seem like an attractive option on closer inspection, are found to be unsuitable.

Next on the list to be considered are the metals: Anodized Aluminium, Titanium and Stainless steel. Metals offer some large benefits over the other materials discussed so far namely that they are less susceptible to sudden catastrophic failure but rather undergo plastic deformation "When comparing metallic and composite pressure hulls, metallic structures generally undergo plastic deformation prior to final failure" (Craven, et al., 2016). As well as that metals are also relatively strong and can withstand the potentially extreme pressures faced during undersee operation, as Semour marine putts it "Titanium is exceptionally strong, lightweight, and corrosion-resistant, even in deep-sea environments. It has excellent fatigue resistance and can withstand high pressures and aggressive fluids encountered in deep-sea operations. By deep-sea, we mean really deep." (Seamor Marine , 2024). Comparing the mentioned metals with each other Titanium offers High strength, low weight and corrosion resistance (Seamor Marine , 2024) but also comes at a cost of about 3 to 5 times more than stainless or aliminium (Craven, et al., 2016) as well as being more complex to fabricate and having a bigger environmental impact than the other metals (Seamor Marine , 2024). Anodized aliminium is another option it offers a cheaper alternative to Titanium and is corrosion resistant due to its coating, Seamor Marine states "Anodized aluminium offers corrosion resistance, durability, and relatively low weight." However the anodized coatings can become damaged leading to corrosion (Seamor Marine , 2024). The final metal to be discussed is stainless steel. stainless steel is heavier than the other metals as well as being less corrosion resistant (Seamor Marine , 2024). Taking these factors into account while metals do offer some large benefits the high cost combined with the difficulty of manufacturing which would also increase cost would not make them a good option as the main goal of this project is to reduce the price of obtaining and operating an ROV.

Another material which could be used Is Polyvinyl chloride (PVC). PVC promises benefits such as being cheap and readily available which is a massive positive for this application as a goal of this project is to reduce the cost of ROVs. As one user on the HomebuiltROVs forum put it, "A nice thing about PVC pipe is its cheap- I don't think I have $50 in this yet, even counting the false starts and junked parts" (Homebuiltrovs, 2022) the statement that PVC is a low cost material is also backed up by an article from Bit Driven Circuits "PVC pipe has the benefit of being cheap which is important if this is your first time constructing an ROV. You may end up junking many pieces of pipe during the process of learning what works and what doesn't." (Bit Driven Circuits, 2021). This is due to PVC being used widely in the plumbing industry which also means it comes in convenient tube shapes which is the main hull shape which was decided on in the previous section. PVC also offers benefits in terms of corrosion resistance as Semour marine puts it "Plastics and composites can offer a good balance of strength, weight, and corrosion resistance." (Seamor Marine , 2024). PVC also has some drawbacks though including not quite living up to the strength and pressure resistance of some of the other materials discussed such as the metal this is mentioned by Semour marine "Plastics and composites may have limitations in terms of depth capability and high-temperature resistance. They might not be suitable for certain deep-sea or high-temperature applications." (Seamor Marine , 2024). PVC's comparatively lower strength and sensitivity to temperature should not be too much of an issue though as this ROV is not going to be built for specialised deep see operation or situations where it may encounter a high enough temperature for it to be a problem as this would hugely increase the cost of the device which directly goes against the main goal of this project. Overall PVC is an attractive option and one which from the information gathered looks like it would be well suited to the application.

Finally, to be discussed is the potential of 3D printing components. 3D printing is a wide field of technology which encompasses many materials such as metals, resins, plastics, and even food but, in this case, I will be specifically discussing Polylactic Acid or as it is more commonly known PLA. PLA is one of the most widely used 3D printing filament types also being one of the easiest to work with

(Raise 3D, 2024). It is also cheap (Wevolver, 2023) which is good for this application. PLA 3D printing works by a process known as Fused Deposition Modelling (FDM) where layers of molten PLA are layered on top of each other to create a part (Carolo, 2024) this method of manufacture comes with the inherent downside that I leads to voids in the parts as one user on the HomebuiltROVs forum puts it "Specific to the 3D printed design: I have concerns about voids in the parts. The fact that 3D printers work by putting down layer upon layer of material (often at less than 100% density) means that there could be small pockets of air in there." (Homebuiltrovs, 2022) This can lead to problems with leakage and structural integrity when it comes to waterproofing and pressure resistance; this is illustrated in the video "Making 3D prints actually waterproof" where it is shown that water can enter the inside of a sealed 3D printed part by seeping through the walls and soaking into the part. It is shown that in some cases 3D printed parts can soak up about 3% to 5% their own weight in water (CPSdrone, 2024). While steps can be taken to make this type of 3D printed part more waterproof this adds extra time and complexity to the process and therefore extra cost which goes against the main goal of this project. Some users on the HomebuiltROVs forum do however provide anecdotal evidence about the abilities of 3D printed parts stating " 3D printed parts should definitely hold up to quite a depth." Other users however state their concern about some of the other drawbacks of 3D printed parts in this context stating with reference to 3D printing "1. LOTS of buoyancy 2. A difficult time making penetrations for wiring 3. A difficult time with sealing the endcaps (which I think is also an issue with the OPENRov design)" (Homebuiltrovs, 2022). 3D printing offers the major benefit however of allowing extremely complex and obscure shapes to be manufactured with ease, this considered 3D printed parts could be a good option for non-loadbearing and non-watertight parts such as brackets, fins, or hydrodynamic additions such as the stern section.

To conclude my discussion on the best materials to use in the construction of this ROV I think PVC pipe is the optimal material to use for the main pressure vessel due to its favourable characteristics discussed previously. As well as PVC I think 3D printed parts would be a good option for other less critical structural components due to its ease of manufacture and low price.

The ROV needs to be able to manoeuvre itself so that it can point the camera at the desired area, and it needs to be able to reach the area being inspected. For this it needs some form of propulsion system. There are two main paths we could go down in terms of propulsion systems biologically inspired propulsion and electrical motor-powered thrusters. Biologically inspired propulsion or in simpler terms the use of a tail to provide propulsion. This system of propulsion offers many benefits over that of traditional thrusters for example "rotary propulsion systems actively suck in objects and wildlife into the propeller, whereas systems with oscillating propulsion pushes obstacles away from its body rather than entangling them" (Sander, et al., 2022) this Is a large benefit in terms of the maintainability and longevity of the ROV. In addition to this biologically inspired propulsion systems also offer much greater efficiency than that of rotary propulsion systems. Where rotary propulsion systems offer an efficiency up to about 40% biologically inspired propulsion systems have shown efficiencies of up to 87% in lab experiments (Sander, et al., 2022). High efficiency is a large benefit as this reduces wasted energy as well as wear and tear on the ROV which decreases the likelihood of failure therefore reducing cost and aligning itself with the project aims. Another benefit is the ease of waterproofing, this is because there are no external parts in direct contact with the water because they would all be contained within the flexible tail (Sander, et al., 2022) therefore reducing the likelihood of water damage. There are downsides to biologically inspired propulsion systems as well however as the paper "OpenFish: Biometric design of a soft robotic fish for high speed locomotion" puts it "Building a robotic fish with satisfactory performance from scratch is a time-consuming process that typically requires extensive tuning of design parameters based on literature research and experiments over the course of many design iterations" (Sander, et al., 2022). This is something that would be complex and costly to achieve. In addition to this the paper also states "On the other hand, designs that make use of a compliant tail (i.e. soft robotic fish) are typically not capable of high speed swimming Moreover, the fabrication of most of these existing designs is complex and tedious" (Sander, et al., 2022).

The other option we have is the use of more traditional propeller thrusters powered by electric motors. There are a few things we must consider when thinking about the underwater use of electric motors which are: what type of electric motor should be used (Brushed or Brushless outrunners) and how will they withstand underwater use. After conducting research on the motors, it was found that due to their constructions brushless outrunner motors are inherently more water resistant than brushed motors due to their construction, as one user on the Blue Robotics forum (which is a resource I was pointed to by a professional team of underwater roboticists at a talk I attended) says "Brushless motors can run fully submerged fully exposed to water, no burn out no short-circuit. I prototype with bare brushless motors often" (BlueRobotics, 2020). Brushless motors do however suffer the disadvantage of requiring an expensive speed controller for each motor in order to function (HomebuiltROVs, 2020) which is a major disadvantage for this project as a main goal is to reduce cost. On the other hand, we have brushed DC motors according to HomebuiltROVs "you can wet-run brushed motors but they won't have a very long life as you say, even in fresh water. In salt water, their life is generally very short." (HomebuiltROVs, 2020) this is also backed up by an article from Autodesk Instructibles which states "Technically small [brushed DC] motors will work okay in submerged in water. But let's be honest. Nobody likes maintenance after every use" (metalhead8711, 2016).

Related to electric motors is the idea that we could use water jets to propel the ROV instead of using propellers. The water jets would be produced by forcing water through a nozzle using an impeller (Gangadharan, 1986). As water is pushed backwards Newtons third law tells us that there will be an equal and opposite push accelerating the ROV forwards (Newton, 1687). A water jet system provides the advantage of not having any external moving parts so it allows it to move through weeded and overgrown areas and areas of high amounts of debris in the water without needing to worry about damage to a propeller (Gangadharan, 1986). Disadvantages however of a waterjet system include not being able to provide the same levels of efficiency as seen in propeller based systems and compared to propeller designs they are more difficult to inspect, maintain, and repair due to the impeller being more tucked away (Gangadharan, 1986). For these reasons a waterjet propulsion system would not be a suitable choice for this ROV.

I decided to conduct an experiment to investigate how well brushed DC motors actually hold up underwater. A small DC motor was salvaged from a broken non submersible toy and soldered to a pair of wires as shown in Figure 3. The solder joints were then sealed to prevent them short circuiting, this is shown in Figure 4. This is important as this way we are only testing the motor and not the wires. The motor was then submerged in heavily salted water and connected to a 1.5V power supply. The results are as follows the motor was left running in the salt water for 6 hours and 11 minutes. It was then removed from the water but not cleaned or dried and left to sit overnight. It was then resubmerged and left to run in the saltwater for another 7 hours and 20 minutes. After this time the experiment was ended due to running out of battery. Overall the motor ran submerged in salt water for 13 hours 31 minutes as well as sitting covered in salt water for many hours between runs. I was extremely surprised to find that at the end of the experiment the motor ran just as well as it did at the start of the experiment and did not show any visible signs of corrosion or damage.

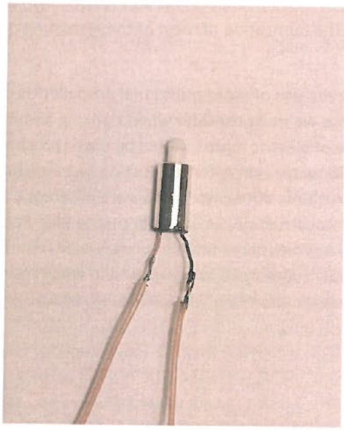


Figure 3

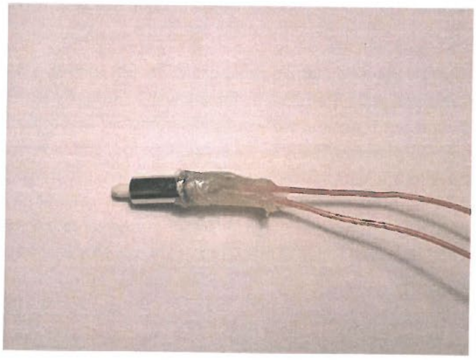


Figure 4

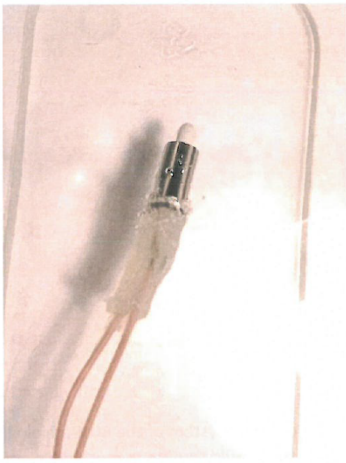


Figure 5

The results of the experiment show that even though brushed motors may be less resistant to water than their brushless counterparts they can still very much be operated underwater for extended periods of time without being damaged. Both kinds of will eventually corrode and become damaged however therefore it is highly recommended that both brushed and brushless motors are thoroughly cleaned and flushed out with something such as WD40 after use (HomebuiltROVs, 2020). Reliability will help to reduce cost in the long run due to not having to constantly perform repairs therefore it is necessary to extend the life of the motors as much as possible. For this reason, some form of waterproofing or water protection would still be appropriate.

One form of waterproofing which could be used is magnetic coupling. This is where the motor is connected to a ring of magnets on the inside then on the outside on the wet side there is another ring of magnets connected to the propeller (HomebuiltROVs, 2020). A concern which could be brought up when talking about magnetically coupled thrusters is how much force could be transmitted before slipping occurs, one user from the HomebuiltROVs forum discusses this "One of my main concerns when designing the magnetic coupling was how much force the magnets would be able to transmit before slipping, but after a bit of trial and error, It takes a surprisingly large amount of force to cause the magnets to slip!" (HomebuiltROVs, 2020). A design for a magnetically coupled thruster can be seen in Figure 6 .

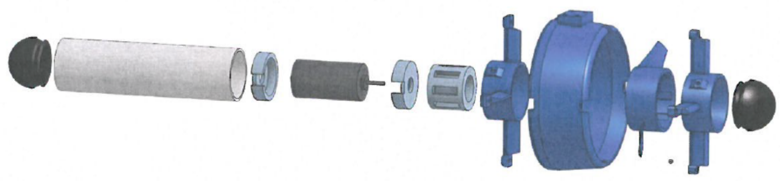


Figure 6 (HomebuiltROVs, 2020).

To conclude this section on the propulsion system of the ROV, a biologically inspired propulsion system would not be appropriate as it would require to much development in order to see its benefits. The best type of electric motor is the DC motor as even though the brushless outrunner may be more resistant to water, they require expensive controllers to operate. On the other hand, DC motors can be controlled with relatively simple electronic circuitry. As well as this the experiment showed that DC motors are also capable of withstanding submersion in water to a certain extent. Even though the motors can be run bare in the water I think it would be advantageous to employ magnetic coupling to provide further protection in order to reduce maintenance and increase longevity and therefore reduce cost.

The ROV must be able to submerge and resurface as well as control its depth in order to meet the project aim of providing underwater surveillance capabilities. To do this it must have a system for controlling its buoyancy. The paper "Experimental Study of a Variable Buoyancy System for low Depth Operation" states "A vehicle's buoyancy can be controlled through two methods: 1) active buoyancy control, which is achieved either by changing its mass in every cycle, or 2) passive buoyancy control, in which dead weight is used to control buoyancy." (Sharma, et al., 2023) Both methods have their advantages and disadvantages which will be discussed. Starting with the active buoyancy control option. Active buoyancy control provides the main benefit of allowing the submersible to control its depth without the need for the propulsion system to be used "Adjustable ballast allows the submersible to grab objects and manoeuvre on the seafloor without the need for thrusters to push it down" (Blue Robotics, 2014), the buoyancy can be set and the ROV can be allowed to float or sink to the required depth. This saves power and avoids causing unnecessary wear and tear to the propulsion system. Additionally, in the case that the ROV device is fitted with systems capable of picking up or dropping objects buoyancy can be adjusted to maintain maneuverability, this is something a fixed or passive buoyancy system would not be able to do. In the case of this project though this is not relevant as the goal is to provide underwater surveillance capabilities, the ability to interact with the surroundings is out with the scope as it would be unnecessary to the aim and add extra cost, time, and complexity.

Active buoyancy control can be implemented in several ways, the most common methods being by having some form of ballast tank or bladder which can be filled and emptied to change the volume of the ROV and therefore the buoyancy. Ballast tanks and bladders can be filled and emptied by the use of a piston or by using a compressed gas to push the water. Starting with the use of compressed gas.

The gas can be stored onboard the ROV then when buoyancy needs to be increased the gas can be released into the ballast tank to force out the water. This approach has some disadvantages for this application though as storing and controlling compressed gasses requires specialized electronics and pressure vessels, as the paper "Dynamic Buoyancy Control of an ROV using a Variable Ballast Tank" putts it "The major components of this system are the air tank used to supply the system and the manifold and solenoid valve assembly used to distribute the compressed air to the system" (Wasserman, et al., 2003). The website Underwaterthruster backs this up by also discussing in slightly more detail the components used "A typical soft ballast system should consist of one or more 3,000 lb. submersible bottles, a decompression regulator, a surface control solenoid valve, and a thin-walled tank" (Fengyukun, 2003). An article by Blue Robotics also brings up another interesting point "One thing I don't like about CO2 is the adiabatic cooling and the tendency for frosting to occur. I would more than likely use an inert gas or dry nitrogen to fill my gas containers with. A rapid release of 250 psi might not seem like much but any moisture in the lines can cause ice formation." (Blue Robotics, 2014). This is in reference to the fact that when a gas rapidly expands it cools down and can cause any residual moisture or water in the ballast tanks to freeze, this is a disadvantage as ice buildup could cause damage and block solenoids or ports stopping the flow of gas and rendering the buoyancy system ineffective. These things considered, the use of compressed gas to control an active buoyancy system would not be a good choice for this application, it may however be the best choice in other situations for example for a larger scale system where a piston or mechanical solution would be impractical, as Underwaterthruster puts it "very large submersibles have blown air ballast tanks to regulate underwater buoyancy." (Fengyukun, 2003). The use of a piston to force water in and out of a ballast tank or bladder is another option that could be used to control an active buoyancy system. The paper "Experimental Study of a Variable Buoyancy System for Low Depth Operation" illustrates how a piston could be used to control buoyancy via a bladder "using the single-stroke piston by injection/extraction of the hydraulic oil to or from the external bladder and controlling the buoyancy by control in the total displaced volume by the vehicles" the paper then goes on to illustrate how the piston could be used with a ballast tank "system by movable plate inside the ballast tank. This resulted in the change in vehicle buoyancy by changing the volume of the ballast tank filled with water" (Sharma, et al., 2023). While the use of a piston to actively control buoyancy could be a good option at this scale it also suffers from high mechanical complexity (Sharma, et al., 2023) which would add cost and provide more potential points of failure and the potential for water ingress causing damage to any electronics if the seals on the piston were to become damaged.

Passive buoyancy control could also be used. In this case the buoyancy of the vehicle would be adjusted to the desired value by adding ballast or floatation prior to use then once set it could not be adjusted on the fly like an active buoyancy control system could. The main benefit of this system is its extreme simplicity, this removes many points of failure while simultaneously also massively reducing cost due to the lack of specialized components and parts which align with the main goal of the project. The fairly obvious downside to this system however is that as previously mentioned buoyancy cannot be adjusted on the go. In order to get the ROV to the desired level of buoyancy ballast or floatation must be added prior to use. One method of increasing buoyancy is by adding foam, careful consideration must be given to using foam though as it is generally compressible so when the submersible dives it will compress causing a loss in volume and therefore buoyancy and potentially leading to the ROV sinking (Blue Robotics, 2014). Buoyancy generally comes from the pressure vessel which contains the electronics and other systems (Fengyukun, 2003) then ballast such as lead blocks can be added to get the required buoyancy. Buoyancy can be calculated using the formula shown in equation 2. As the website Underwaterthruster puts it "The fixed load on the submersible is usually in the form of several lead blocks." (Fengyukun, 2003). The ballast can also be adjusted to control the trim of the vehicle, this can be achieved by the inclusion of compartments internally within the hull. The inclusion of compartments also benefits the robustness of the ROV as Underwaterthruster puts it "Submersibles constructed using sealed tubular frames for buoyancy can be damaged during operation. It is therefore common to have multiple compartments in the frame to ensure that a significant amount of buoyancy is not lost in the event of damage" (Fengyukun, 2003). The ideal buoyancy is slightly above neutrally buoyant that way in the event of a failure the ROV would automatically return to the surface (Fengyukun, 2003). Neutral buoyancy also provides the least resistance to change in depth which would be controlled by the thrusters "having the ROV neutrally buoyant and having a vertical thruster (or three) works fine" (Blue Robotics, 2014) this is backed up elsewhere in the text by another user who says "I think the vertical thruster could work alright and waste relatively little energy if you can manage to make the ROV neutrally buoyant" (Blue Robotics, 2014).

$$F_b = -\rho g V_f$$

$$F_b: Buoyant\ force$$

$$\rho: Fluid\ density$$

$$g: Acceleration\ due\ to\ gravity$$

$$V_f: Volume\ of\ fluid\ displaced$$

Equation 3

In conclusion after careful assessment of the techniques available I have decided that the best option for this project is to implement a passive buoyancy system and have depth controlled by the thrusters. While an active variable buoyancy system would provide a greater degree of control I feel the complexity it adds out ways its benefits and since a main goal is reducing cost this is not the best option.

There were many things to consider when researching the control system these include; how are instructions going to get from the operator to the ROV, how is the ROV going to be powered, how will the instructions from the operator be processed and carried out, how will the camera collect and send data and how can all this be done for the lowest practical price.

Starting with how the instructions are going to get from the operator to the ROV. There are two main paths we could take wireless or tethered. The paper "A Survey of Underwater Wireless Communication Technologies" states that there are three main method that could be used to achieve submarine wireless communications these are radio frequency communications (RF), acoustic frequency communications (AF), and optical communication (Gussen, et al., 2016), all have benefits and disadvantages. we face some challenges when it comes to underwater radio communication as the paper "A Survey of Underwater Wireless Communication Technologies" states "From the physics viewpoint, for frequency ranges employed by mobile services, TV, radio, and satellite communications, the seawater is highly conductive, thus seriously affecting the propagation of electromagnetic waves" (Gussen, et al., 2016). This is illuding to the fact that the most commonly used frequencies; HF (High Frequency 3MHz – 30MHz), VHF (Very high frequency 30MHz – 300MHz), and UHF (Ultra high frequency 300MHz – 3GHz) are highly attenuated by seawater due to its properties and therefore greatly negatively impact their useful underwater range. For this reason, frequencies in the ELF (Extremely low frequency 3Hz – 300Hz) or VLF (Very low frequency 3KHz – 30KHz) ranges must be used. The disadvantage of this is as the paper "A Survey of Underwater Wireless Communication Technologies" puts it "communication in ELF and VLF frequency ranges has operational and financial difficulties, since the equipment is large, expensive and requires high power" (Gussen, et al., 2016). It goes without saying that large, expensive, and high-powered equipment would not be an appropriate choice for this project as the main goal is to reduce the cost of ROVs. Moving on to optical communications (that is the use of light to transfer data). A big advantage of optical communication underwater over radio is the range that can be achieved. The light used to provide optical communications can be produced in several ways either by the use of LEDs or lasers, lasers have the advantage of having a greater range than LEDs but also come at a greater price (Gussen, et al., 2016) which is a large disadvantage in the case of this project. Optical communication also suffers the disadvantage of the data quality being affected by conditions in the water such as turbidity (Gussen, et al., 2016) in addition to this it also requires a direct line of sight between the transmitter and receiver so could be easily interrupted by for example the passage of marine life (Gussen, et al., 2016). The optical communication must be received in some way this can be done through the use of specialised electronic components the paper "A Survey of Underwater Wireless Communication Technologies" states "The main photosensor types are: photoresistors, photothyristors, phototransistors, photomultiplier tube (PMT), p-n photodiodes, avalanche photodiode (APD), photon detector selection, semiconductor photosensors, and biologically-inspired quantum photosensors (BQP)." As well as requiring complex optics, the paper then goes on to say that these sensors can be expensive and bulky which is a major disadvantage for this project (Gussen, et al., 2016). Acoustics are another option for wireless communications. Out of all the underwater wireless communication methods discussed so far this is the one that can provide the greatest range (Gussen, et al., 2016) for example some low frequency parts of whale song (which is a form of underwater wireless communication) can travel up to 8000 kilometres (Wilkins, 2022) which is many orders of magnitude greater than the distance achievable by RF or optical communication. It is due to this reason that acoustic communication is currently the dominant form of underwater wireless communication used today (Gussen, et al., 2016). There are disadvantages to acoustic communication as well though one of which being distortion as the paper "A Survey of Underwater Wireless Communication Technologies" puts it "Signal propagation is another relevant issue in underwater acoustic communication. Multiple delayed and distorted versions of the transmitted signal arrive at the receiver due to the multipath channel" (Gussen, et al., 2016) this is shown in Figure 7 . Another disadvantage is latency in communication (Gussen, et al., 2016) as the speed of sound in water is much slower that the speed of light (and RF) in water (speed of light in water being $2.25 \times 10^8\ ms^{-1}$ (BYJU'S, 2023) and the speed of sound in water being $1500 ms^{-1}$ (NOAA, 2022)). Also closely linked to the speed of sound in water is the greater potential for problems due to Doppler shift (Gussen, et al., 2016).

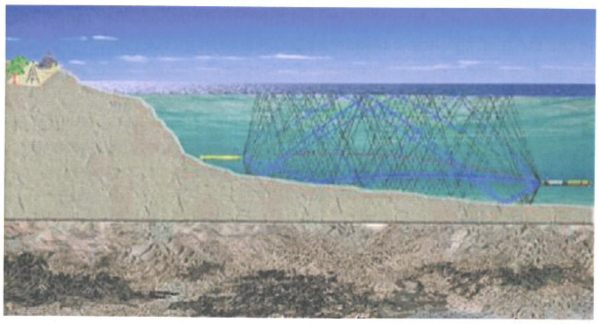


Figure 7 (Gussen, et al., 2016)

The other option apart from wireless communication for sending instructions from the operator to the ROV is the use of a tether. A common standard used for the construction of ROV tethers is cat5 cable (also commonly referred to as ethernet cable) which consists of four twisted pairs of wires (Wikipedia, 2024). Cat5 cable is advantageous because as one user on the Arduino forum puts it "As far as communication, in theory you could use ethernet for everything (audio, video, data and control)." This is also backed up by another user who states "You should be able to do every thing over the existing cat5 wire" (Arduino, 2010). It is also widely used in computer networking (Wikipedia, 2024) so is easy to come by and relatively cheap " you can send video over cat5 cable easily (and its cheap)" (Homebuiltrovs, 2023) which is advantageous as one of the main goals of the project is to reduce the cost of ROVs. A potential disadvantage of a tethered communication system is the limit it puts on range and the potential for entanglement due to having a tether trailing behind itself. these things considered the use of tethered communication through the use of cat5 cable is the more advantageous option to this project over all forms of wireless communication discussed as while they may offer greater freedom and range, they also come at the cost of high complexity and high price. On the other hand, the use of a tethered cat5 system offers simplicity due to not requiring complex signal processing (Gussen, et al., 2016) and is cheaper and easier to obtain.

Next on the list to be discussed with reference to the control system is the issue of how the ROV is going to powered. Will the power system be shore based and send power to the ROV via the tether or will it be onboard, and what type of battery is best? In terms of whether the power system should be onboard, or shore based both have their advantages and disadvantages. Shore based power offers the main advantage of being able to continuously operate and recharge the ROV without the need to return to the surface allowing for potentially indefinite dive time. There are some disadvantages of shore-based power though the main one being the need to send the power to the ROV via the tether which could cause problems for the other systems as one user on the HomebuiltROVs forum puts it "I have heard mixed reviews and comments about sending power AND video signal down the same Cat5 cable... there tends to be a few issues with noise. I know in industrial applications (which is what I do in my day job) it is a huge No No!" (Homebuiltrovs, 2023). There is also the problem that there may be high current draw due to the need to power high demand parts such as motors which could cause heating and damage due to the relatively thin conductors in cat5 cable. A user on the HomebuiltROVs forum has this to say "If you want decent thrust you should probably go with batteries on-board" (Homebuiltrovs, 2023). For these reasons I think onboard power is the better option as even though this will limit dive time it mitigates the problems of sending both power and data over cat5 cable.

Once the instructions have been sent down the tether from the operator to the ROV they must be possessed and carried out. There are a number of ways this could be done namely the use of microcontrollers or single board computers such as the Arduino or Raspberry pi series of boards to prosses commands sent by the operator then send signal onwards to the relevant parts of the ROV for example sending a PWM signal to the motors or pure electronic circuitry and analogue processing could be used both have upsides and downsides which will be discussed. Digital processing with the use of a microcontroller such as an Arduino offers some benefits over an analogue solution, most prominently is the fact that they can be reprogramed in the case that something needs to be updated or changed, this is something you would not be able to do with an analogue solution. One user on the Arduino forum says "To start you would probably want 2 Arduinos... One on the rover as the controller and one as the remote control" (Arduino, 2010) in this case the on-shore Arduino would take in the inputs from the user then convert them to some form of data signal and send them down the tether to the onboard Arduino which would decode the data and then act on it, simultaneously the onboard Arduino would be encoding the video output which would then be sent up the tether to the shore-based Arduino which would decode and display it. One user on the Arduino forum says "You would then communicate to the rover with some sort of data protocol, probably a minimum of 2 wires, ground and data" (Arduino, 2010). In the case of this project a minimum of 3 wires would have to be used, those being ground, control, and video. Using microcontrollers does have disadvantages as well though. First of in general a microcontroller is a more expensive option than analogue processing, on top of this a microcontroller is also significantly more difficult to repair than an analogue option. Using a microcontroller would also require software and data protocols to be written, which adds extra complexity. On the other hand, we have an analogue solution. An analogue solution may include something along the lines of a signal being sent down the tether which then switches relays to control the motors as a user from the Arduino forum describes it "Its controlled by a cat5 tether and a simple system of relays for forward - off - reverse of each axis of movement. A camera sends video over a pair of wires in the cat5 cable via video baluns" (Arduino, 2010), this extract also brings up the point that the video signal could also be sent via analogue means. An analogue solution has the main benefit of being simpler and therefore easier to repair as well as being cheaper to construct and not requiring complex software to be created. Being easier to repair will also reduce the overall cost as it will extend the life of the device and not require a new device to be purchased. The downside however of an analogue solution is that its functionality cannot be drastically changed or updated once it is constructed.

Another important part of the control system is the camera. It could be argued that this is in some ways almost the most important component as without it the ROV would be almost entirely pointless. As one of the main design goals is to provide underwater surveillance capabilities the camera is of utmost importance. Once again there are two paths, we could take: analogue or digital. A popular option is to use an IP camera "I would use the Arduino Mega and IP Camera on the UAV and a laptop for control. The Arduino Mega would have some sort of ethernet interface (ethernet shield) and serve up a webpage that used some javascript to show all the information I wanted to see. This webpage would also include an iframe that would show the live video from the IP Camera" (Arduino, 2010). An IP camera is one which has an internal 'server' of sorts which can then be connected to via a web browser to view the output (Homebuiltrovs, 2023) this data can be sent over the cat5 cable from the ROV to the user (Arduino, 2010). The use of an IP camera however does require the use of other components such as microcontrollers to prosses and send data "Three items needed for viewing and control:

1. IP camera ($60 purchased from large online retailer in Australia), warranty voided and two wires soldered on.
2. Microcontroller board with VERY simple program (Atmel M32 programmed in BASCOM, alternatively use Arduino or any similar) to receive serial out from the cam board and convert it to thruster speed control PWM signals.
3. PC running browser to view camera, and to send ROV commands from a simple HTML file on the PC ($200 ASUS netbook works well)" (Homebuiltrovs, 2023). We can see from this extract that the use of IP cameras can get expensive and also requires the presence of a computer on shore to view the video signal which will also add a significant portion to the cost of operation which goes against the original design goal of this project. On top of this IP cameras may need some modification to suit the required use case which adds complexity as one user (Homebuiltrovs, 2023). The other option is analogue video. Analogue video output would simplify the required components greatly, not requiring a computer with a web browser to view or complex software. Analogue video can also be sent over a single pair of wires freeing up the others in the cat5 for control of the ROV as one user on the Arduino forum says "A camera sends video over a pair of wires in the cat5 cable via video baluns" (Arduino, 2010) the fact that analogue video can be sent over cat5 cable with the use of video baluns is also backed up by another user from the HomebuiltROVs forum who says "I am coaching a kid team building their first ROV...for this first version we are running power/video in a single CAT5 using passive Baluns at each end" (Homebuiltrovs, 2023) a diagram of the setup for sending video over cat5 cable can be seen in Figure 8 . Another advantage of using analogue video is the availability off the shelf components used in security systems such as the cameras themselves and the video baluns, this leads to lower cost and ease of repair as replacement parts are readily available, an analogue system is also simpler and therefore easier to maintain than the digital system therefore also reducing cost.

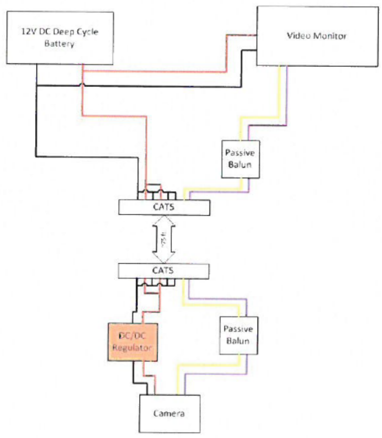


Figure 8 (Homebuiltrovs, 2023)

The ROV could potentially be required to operate in low light conditions, so some form of lighting is also required. LEDs can be used for this purpose as they are cheap and power efficient. The optimal placement for lights to allow for the clearest view from the camera is to have them as far away from the camera as possible as that way any light from contaminants in the water is not directly reflected back into the camera (CPSdrone, 2023).

To sum up my findings on the control system of the ROV I have concluded that the most optimal way to send data between the operator and the ROV is through the use of a tether (more specifically the cat5 standard of cable) as this option is orders of magnitude simpler and cheaper than submarine wireless communications which are complicated and expensive. The ROV will be powered by the use of onboard batteries because even though on shore power does promise the big advantage of extended dive time it also cases issues with interference with other systems and may damage the thin conductors within a cat5 cable. The operator's instructions will be processed and carried out by analogue electronic circuitry as this provides a cheaper, simpler, and more easily maintained system than the use of microcontrollers. While microcontrollers do provide the benefit of being easier to update it could be argued that the benefits to this project of the analogue solution outweigh the benefits of microcontrollers. The Camera system will be comprised of an analogue camera which sends its data via a pair of video baluns over the cat5 tether to the operator. The analogue video solution was chosen because it provides a cheaper, simpler and more easily maintained alternative than the use of an IP camera system.

Finaly, we come to the waterproofing. The ROV must be waterproof to protect the sensitive electronics inside. Research had to be done on several different situations namely: how to waterproof permanent joints, how to waterproof through holes for cables, how to waterproof non-permanent joints, and how to protect the electronics from water. It is important to give careful consideration to adhesives and sealants as the paper "Analysis of bonded joints for small craft and marine applications" puts it "A ship (and a small craft for that matter) is a heavily loaded dynamic structure and structural failures are typically caused by abnormal overloading or fatigue. More often than not, these failures occur at connections and interfaces, and very rarely in the bulk material sections" (Armeanu, 2010). One substance which could be used is epoxy resin as one user on rovmaker states "the user must use epoxy resin to fill the gap in the waterproof inside joint." (rovmaker, 2022). Epoxy resin offers the advantage of being strong and widely available (Copps Industries, 2024). More care must be taken when calculating the dimensions of bonded joints to withstand the required forces this is because as "Analysis of bonded joints for small craft and marine applications" puts it "the stress distribution in glued bonds are complex and higher safety factors are required than in other structural materials." (Armeanu, 2010). The solution for waterproofing through holes for cables is very similar to the solution for waterproofing permanent joints. That is the use of adhesives such as epoxy. An additional point which must be considered when talking about the waterproofing of cable through holes is that they are more likely to bend and move around (especially in the case of the tether) so a sealant must be chosen which will maintain strength and integrity and not crack even when repeatedly bent around. This is a disadvantage of epoxy as when cured it tends to be hard and have poor flexibility (Gibbons, 2016). In this case some form of silicone based sealant may need to be used in these cases as silicone sealants offer the advantages of high bond strength and permanent flexibility (Akfix, 2019). It must be possible to open up the ROV to access the electronics and charge the batteries therefore non-permanent waterproof joints must also be developed. This can be done by using O-rings or gaskets. Wikidot states that "A box with a gasket is a simple way to make a waterproof casing that is easily accessed" (Wikidot, 1997). The way a gasket or O-ring seal works is It is deformed by pressure to fill a groove and so creates a watertight seal (rovmaker, 2022). The advantage of using this method of sealing is that it is non-permanent so can be used for example round hatches which can be opened and closed to reach parts on the inside of the ROV. One of the more potentially expensive parts of the ROV will be the electronics therefore they need to be protected from potential water ingress. One method this could be done is by 'potting' the electronics this is where they are encased in resin or other sealant (Wikidot, 1997). An advantage of this is that it provides a great degree of protection to the electronics both from physical damage and from water, practically guaranteeing no water will reach the electronics. A downside of potting however is that the electronics cannot be accessed after the fact so if a component were to malfunction the whole board is practically a write off (Wikidot, 1997). The ability to simply perform maintenance reduces costs so is of benefit to this project, unfortunately however potting effectively prohibits maintenance of the electronics so would not be a good option for the ROV. An alternative to potting is to coat the components is some form of oil (Wikidot, 1997) this could be as simple as a spray of WD40 once in a while. This provides a protective barrier in the case of water ingress. Another step which could be taken to protect the electronics from water ingress is suspending them in the middle of the hull rather than having them sitting on the bottom where water would gather if it leaked in (Wikidot, 1997). Channels could then be provided for the water to flow past the electronics and gather away from them in the bottom of the hull.

Specification

1. chassis/ hull.

1.1 Bow / Front Section.

1.1.1 The front of the hull should be hemispherical in form.

1.1.2 The front section should be transparent to allow a view for the camera.

1.1.3 The front section should be able to withstand a pressure of up to 5 atmospheres.

1.1.4 The front section should be waterproof at a pressure of 5 atmospheres.

1.2 Mid-section.

1.2.1 The mid-section will be cylindrical in shape.

1.2.2 The mid-section should be able to withstand a pressure of 5 atmospheres.

1.2.3 The mid-section should be waterproof at a pressure of 5 atmospheres.

1.3 Stern.

1.3.1 The stern section should have an external geometry of a rounded-tapered shape.

1.3.2 The stern section should be waterproof to a pressure of 5 atmospheres.

1.3.3 The stern section should be able to withstand a pressure up to 5 atmospheres.

2. Construction materials.

2.1 The main Pressure vessel will be constructed from 125mm PVC pipe.

2.2 Non watertight components will be constructed from 3D printed PLA.

3. Propulsion system.

3.1 The propulsion system should provide enough power to maneuver itself to the required destination. (more than 0.02N, see mathematical modelling and analysis section)

3.1.1 The propulsion system should be able to alter depth.

3.1.2 The propulsion system should be able to move the ROV fore and aft.

3.1.3 The propulsion system should allow the ROV yaw control.

3.2 The propulsion system should be able to operate submerged up to a pressure of 5 atmospheres.

3.3 The propulsion system will use a DC brushed motor.

3.4 The electric motor will be protected from the environment using magnetic coupling.

3.4 The propulsion system should be fully controllable by the operator.

3.5 The propulsion system will be electrically powered.

4. Variable buoyancy system.

4.1 There shall be ballast compartments to allow weight to be added.

4.1.1 The compartments should allow enough weight to be added to make the ROV neutrally buoyant (weight is equal to the buoyant force).

4.2 The compartments should be adequately spread such that the trim of the ROV could be adjusted.

4.3 The ballast compartments should be easily accessible to allow for adjustment.

4.4 The main pressure vessel will provide the positive buoyancy.

4.5 The ROV should have a passive buoyancy system.

5. Control system.

5.1 Tether.

5.1.1 The tether should be able to transmit instructions from the operator to the ROV.

5.1.2 The tether should be able to transmit video signals from the ROV to the operator.

5.1.3 The tether will be made from the cat5 standard of cable.

5.1.4 The tether should be able to be submerged and still operate as intended.

5.1.5 The tether should interface with both the shore control unit and the ROV.

5.2 Power.

5.2.1 The ROV will be powered by batteries.

5.2.1.2 The batteries will be stored onboard the ROV.

5.2.1.3 The batteries should be easily accessible.

5.2.1.4 The batteries should be rechargeable.

5.3 Prossesing.

5.3.1 The processing system should be able to get instructions from the operator.

5.3.2 The processing system should be able to control the ROV's systems based on the instruction from the operator.

5.3.2.1 The system should be able to turn of and on the lights.

5.3.2.2 The system should be able to control each of the motors independently.

5.3.2.3 The processing system should be able to run the motors in both directions.

5.3.3 The processing will not be constructed using microcontrollers instead making use of discreate electronic components and analogue processing.

5.3.4 The system should be able to send instructions from the operator down the tether.

5.4 The ROV should provide underwater surveillance capabilities.

5.4.1 There should be a Camera system.

5.4.1.1 Camera system should be able to provide a clear image from the front of the ROV.

5.4.1.2 The camera system should provide video output.

5.4.1.3 The camera system should be able to send its signal up the tether to the operator.

5.4.1.4 The camera system should send its signal via a pair of video baluns.

5.4.1.5 The camera system will be analogue.

6. Waterproofing.

6.1 permanent joints.

6.1.1 permanent joints will be waterproofed using Epoxy.

6.1.2 Permanent joints should be waterproof at a pressure of 5 atmospheres.

6.2 non-permanent joints.

6.2.1 non-permanent joints will be sealed using O-rings and gaskets.

6.2.2 non-permanent joints should be waterproof at a pressure of 5 atmospheres.

6.3 through holes.

6.3.1 Through holes will be sealed using flexible silicone sealant.

6.3.2 Through holes should be waterproof at a pressure of 5 atmospheres.

6.4 electronics.

6.4.1 The electronics should be suspended in the middle of the pressure vessel.

6.4.2 There should be room for water to flow down past the electronics inside the pressure vessel.

7. The ROV should be constructed for a low as possible cost.

8. The ROV should have as low as possible operating expenses.

9. The ROV should be easily repaired and maintained.

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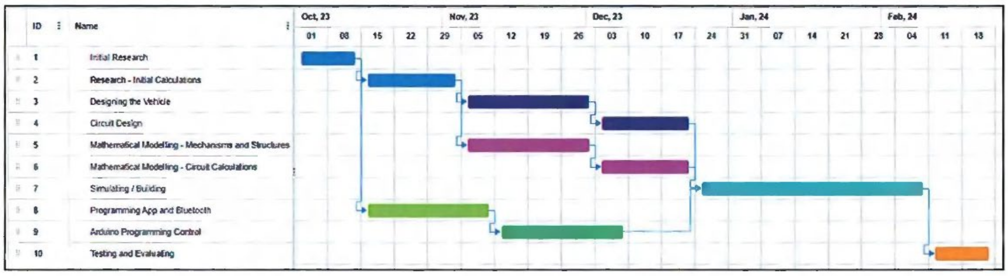
Production and maintenance of a detailed project plan

Project Plan

Gantt Chart 1



This is the first gantt chart which was developed at the start of the project. We were initially told that the project should be completed by mid February, it was extremely ambitious hoping to complete the project and build it in this timeframe.

List of actions

- The initial research must be done, this will include:
    - Research into fire hoses, and fire nozzles including their properties
    - Research into the pressure and flow rates from fire hydrants
    - Research into the temperatures in burning buildings and materials which could be used that would withstand these temperatures
    - Research into ways of communicating with the vehicle remotely
    - Research into motors which could be used
    - Research into electronic components which could be used
- Initial calculations from the research, this will include:
    - Calculating the forces which will act on the vehicle due to the fire hose
    - Calculate the required mass of the vehicle and the mass that the motors must move
    - Calculating the required torque of the motors and determine suitable motors
- Mechanical mathematical modelling
    - Complete mathematical modelling of all the major mechanical components including:
        - Torque and power calculations of all motors
        - Gear forces calculations
        - 3D angled forces for the axle
        - Shear force diagram for axle
        - Bending moment diagram for axle
        - Stress and second moment of area calculations
    - Create a CAD model of the vehicle
- Electronic mathematical modelling
    - Complete mathematical modelling of all major electronic and control components:
        - Circuit calculations of the resistor, current, and voltage values required for each electronic component and each motor to allow them to rotate at the right speed and torque
        - Voltage and capacity battery requirements
        - Calculations of any other electronic circuits
    - Design the electronic circuit for the vehicle
- Programming control
    - Programming the control of the vehicle
    - Programming the communication between the app and the vehicle
    - Creating an app to control the vehicle
- Complete mathematical modelling of any other system after research
- Simulation of all the major systems and construction of the vehicle
- Testing and evaluation of the vehicle

Resource Requirements

Due to the time constraints and due to the budget constraints, it would be impossible to build the vehicle itself so instead, a model will be made. Therefore some of the more difficult materials to obtain stated in the outline will not be required for this project like: Strong fireproof materials for the body, fireproof wheel materials, fire hose and nozzle, fire hydrant.

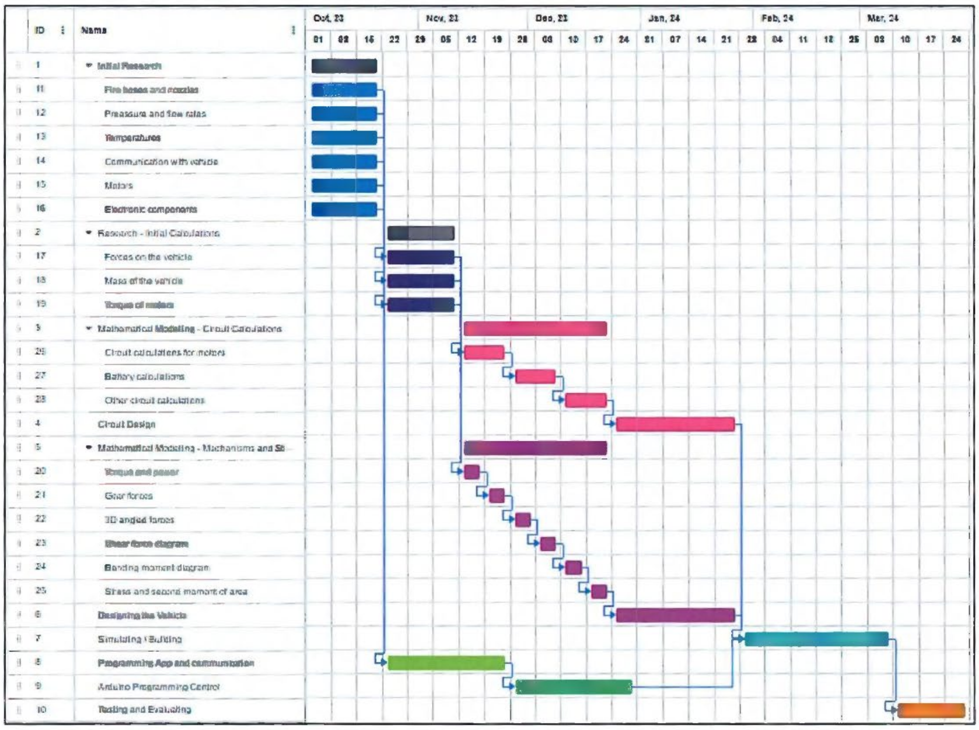
Other materials like the Arduino microcontroller and other electronics should be ordered immediately after the initial research. This would allow the communication between the device and vehicle, and the control of the vehicle to be programmed as soon as possible. There is however a lot of float time so it is not strictly necessary to order these materials immediately, but it would mean that there would be no delays due to parts not arriving.

There are many suppliers which could provide these electronics, most of them being Chinese, but ordering from China would put a massive halt due to delivery times so they should simply be ordered from Amazon or other similar suppliers.

The mechanical parts required for the actual design of the vehicle such as motors would likely be very expensive. For the model or testing purposes, simple DC motors would do fine but the torque should be scaled down with the model. The battery capacity should also be scaled down with the model. These parts should be ordered as soon as the mathematical modelling for them is complete so that they would arrive in time for the simulation / building stage.

Gantt Chart 2

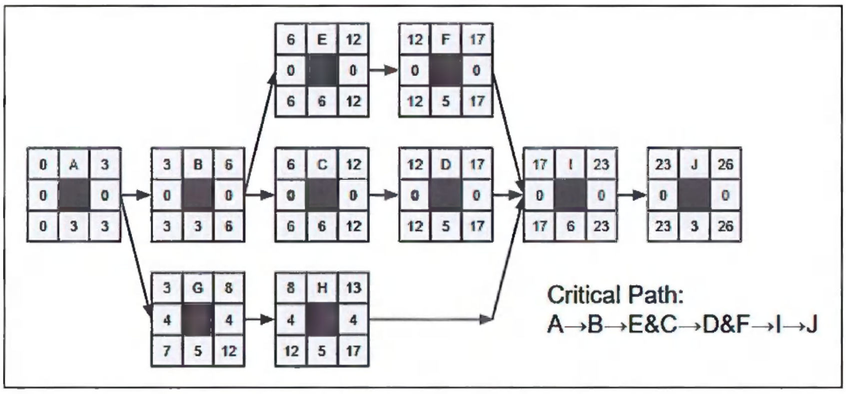
After outlining the main actions of the project, it was obvious that the entire project could not be completed in the short time frame given so the deadline was extended to mid march. This allowed me to spread the workload over a larger period of time. This second gantt chart should hopefully provide a guideline for when each step should be completed. I will attempt to follow this timeline as well as possible.



Critical path analysis

Task	Name	Dependencies	Duration
A	Initial Research		3 weeks
B	Research - Initial Calculations	A	3 weeks
C	Mathematical Modelling - Electronics	B	6 weeks
D	Circuit Design	C	5 weeks
E	Mathematical Modelling - Mechanisms and Structures	B	6 weeks
F	Designing the Vehicle	E	5 weeks
G	Programming App and Communication	A	5 weeks
H	Arduino Programming Control	G	5 weeks
I	Simulating and Building	D, F, H	6 weeks
J	Testing and Evaluating	I	3 weeks

EST	Task	EFT
Float		Float
LST	Duration	LFT



Research Plan

What needs to be researched	*How it is going to be researched*
Research types of available fire hose nozzles and fire hoses and their suitability for this project	Look at the available and most commonly used fire hose and their dimensions on a government website, and google advantages of different nozzle types to determine the most suitable one
Research the flow rates and pressures of water from a different fire hoses in the UK and determine suitable values	Look at national guidance documents on fire hydrants, and look at official fire hydrant tests by the government
Research the spray coverage for the selected nozzle type	Look at articles on spray nozzles from qualified companies to determine the optimal spray angle
Research ways for the operators device to remotely communicate with the microcontroller on the vehicle	Google different communication methods like bluetooth, BLE, radio communication, and infrared communication and determine the most suitable
Research the average temperature that will be exerted to the vehicle in a building	Read different articles from different sources on the temperatures within fires and burning buildings
Research materials which would be suitable for the wheels which would withstand a high temperature	Investigate different tyre materials that have been used in various circumstances, investigate their properties and determine if they could withstand the high temperatures
Research the frictional force acting on the vehicle and research the coefficient of friction between the tyres and the floor	Look at articles and tables of values of coefficients of friction for different similar materials
Research different materials which could be used for the body of the vehicle	Online research to find tables of different materials and their properties to determine a suitable one
Research different motors and in which circumstances they would be effective to use	Look at websites and read articles which compare stepper motors, DC motors and servo motors to determine the most suitable type
Research and select motors to use	Visit motor industrial web stores, find motors which could be used by considering the torque, speed and velocity ratio
Research steering mechanisms	Read articles on how steering mechanisms work and determine a suitable motor which could be used
Research electronic remote communication modules	Read articles on the suitability of the modules and the function of the pins, visit online web stores to compare and find suitable modules
Research electronic modules for streaming video	Read articles on the suitability of the modules and the function of the pins, visit online web stores to compare and find suitable modules

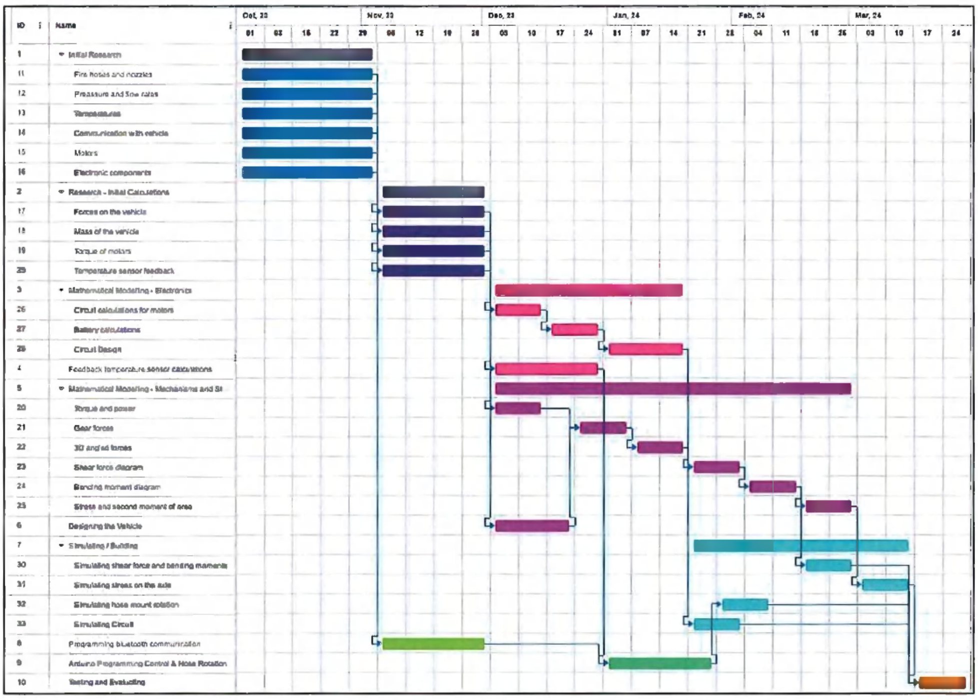
Project Plan

Gantt Chart 3

I have failed to follow the gantt chart timeline for completing the research, unfortunately it took substantially longer than I originally intended it to take. This delay was mainly due to the workload from other subjects. If this were a real life situation with very strict deadlines, delays like this should never happen and could cause significant harm to the business of cooperation. I will hence try my best to follow the new gantt chart and hopefully there will be no more delays such as this.

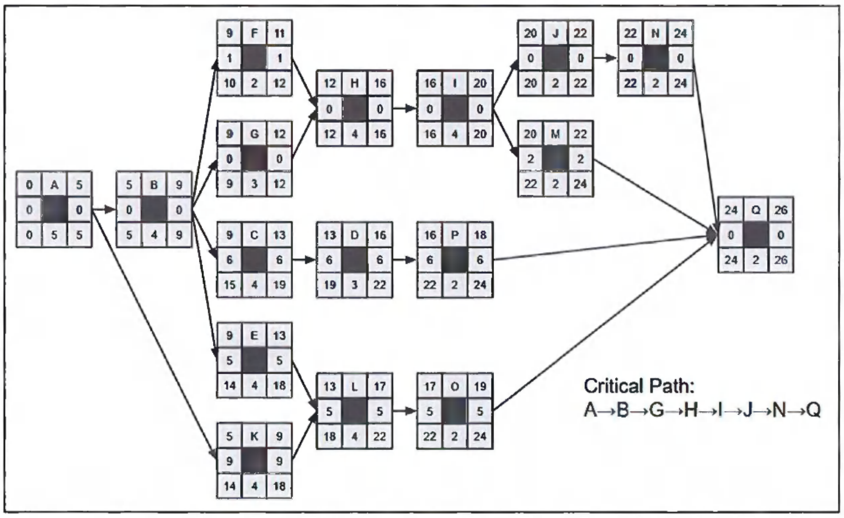
It was clear from the research that more time should be allocated to mechanical mathematical modelling and less to electronic mathematical modelling. Because of this, and because of how long the research took, it is clear that there would not be enough time to mathematically model all the major components and then build a real life model of the vehicle. Insead, all the major components should simply be individually simulated. Since a model of the vehicle will no longer be developed, the design of the vehicle does not need to be so detailed with the result of all the mechanical mathematical models. Instead, the vehicle could be designed right after the research to help with the gear forces and all other mathematical models.

After completing the research, one of the major electronic components, the camera module, has been replaced by temperature sensors. This means programming a new app would not need to be created. It would also mean that the electronic mathematical modelling would include the calculations for the feedback temperature sensors, programming the control would depend on this to be completed first.



Critical path analysis

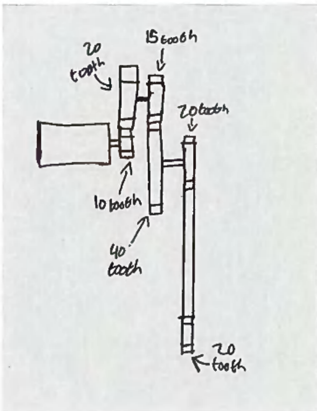
Task	Name	Dependencies	Duration
A	Initial Research		5 weeks
B	Research - Initial Calculations	A	4 weeks
C	Electronic Mathematical Modelling (Circuit & Battery Calculations)	B	4 weeks
D	Circuit Design	C	3 weeks
E	Rotation of Hose Mount Mathematical Modelling	B	4 weeks
F	Torque and Power Mathematical Modelling	B	2 weeks
G	Designing the Vehicle	B	3 weeks
H	Gear Forces & 3D Forces Mathematical Modelling	F, G	4 weeks
I	Shear Force and Bending Moment Diagrams	H	4 weeks
J	Stress and Second Moment of Area Calculations	I	2 weeks
K	Programming Bluetooth Communication	A	4 weeks
L	Arduino Programming Control & Hose Rotation	E, K	4 weeks
M	Simulating Shear Force and Bending Moments	I	2 weeks
N	Simulating Stress and Second Moment of Area	J	2 weeks
O	Simulating Hose Mount Rotation	L	2 weeks
P	Simulating Electronic Circuit	D	2 weeks
Q	Testing and Evaluating	M, N, O, P	2 weeks



Mathematical modelling and analysis

Mathematical Modelling

Mechanical and Structural Models



Gear Mechanism and Forces

This is my design for the gear system that will be used in the climbing treadmill. By using a compound system versus a simple gear train I am able to easily model the velocity ratio (VR) of the system. This also means I could easily change the torque and velocity of the output gear on the belt, which in turn allows me to easily understand and analyse how much force is being applied to the motor through the shaft.

To calculate the VR I used

$$VR = \frac{N_2}{N_1} \times \frac{N_4}{N_3} \times \frac{N_6}{N_5}$$

Where N is the number of teeth on each gear. This allows me to calculate the compound VR which means that with any speed input I can calculate what the output of the system will be.

$$VR = \frac{20}{10} \times \frac{40}{15} \times \frac{20}{20}$$
$$= 2 \times \frac{2}{3} \times 1$$
$$= 5.33$$

For the design shown in the diagram, this means that with any input speed from the motor the output speed will be 5.33 times faster. This is a reasonable value (see specification 2.3) as there is a selection for the size of gears which allow for various rotational speeds in the system.

With this VR the torque of each gear can be calculated using:

$$P = 2\pi nT$$

Where P is power, n is number of revolutions per second and T is torque

$$T_1 = \frac{P}{2\pi n} \qquad \frac{T_2}{T_1} = \frac{N_2}{N_1} \qquad \frac{T_4}{T_3} = \frac{N_4}{N_3}$$

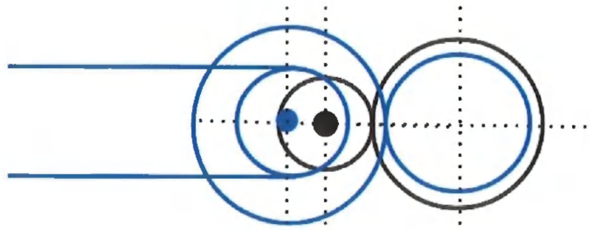
$$T_1 = \frac{300}{2\pi \times 10} \qquad \frac{T_2}{4.77} = \frac{20}{10} \qquad \frac{T_4}{9.55} = \frac{40}{15}$$

$$T_1 = 4.775Nm \qquad T_2 = 4.775 \times 2 \qquad T_4 = \frac{8}{3} \times 9.54$$

(In this case $T_2 = T_3$ as they are connected) $T_2 = 9.55Nm = T_3$ $\quad T_4 = 25.466667Nm$

therefore they have the same torque $T_4 = 25.47Nm = Belt\ Torque$

These torques can be used to calculate the forces applied to the motor shaft that may add/counteract to a portion of its downward force due to its weight. However, before this can be calculated the diameters of each gear needs to be known.



A diagram of the gears shows how they will be configured and shows how the forces will affect the motor shaft (the blue gears are the gears that are in front).

I have acquired the values of r (radius) and θ (pressure angle) directly from an RS Pro data sheet:

$T_2 = Fr$

$9.55 = F \times 11 \times 10^{-3}$

$F_{t2} = 868.181818$

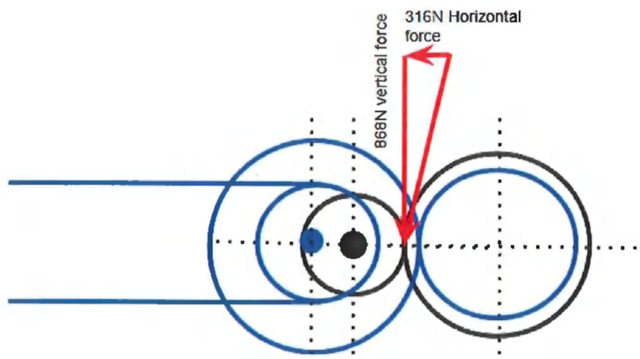
$F_{t2} = 868N$

$F_{r2} = F_{t2}tan\theta$

$F_{r2} = 868tan20$

$F_{r2} = 315.9923397$

$F_{r2} = 316N$



With these calculations it means that using Pythagoras a total force and direction of the force can be calculated:

$$total\ force = \sqrt{(F_{Vertical})^2 + (F_{Horizontal})^2}$$

$$F_{total} = \sqrt{868^2 + 316^2}$$
$$F_{total} = \sqrt{853280}$$
$$F_{total} = 923.7315627N$$
$$F_{total} = 920N$$

This value can be used to give an indication of the forces present when the motor is moving at 10 revolutions per second. This is an applicable pace needed when the wall reaches its maximum speed (as described in the specifications (see 4.2)). However there will be a change in output forces as the wall accelerates and decelerates . Separately we can also calculate the speed used in rps (revolutions per second) and a more usable m/s (metres per second)

$$output\ rps = \frac{input\ speed}{VR} \Rightarrow xm/s$$
$$1\ revolution = 2\pi r\ meters$$
$$\therefore (\frac{10}{5.33}) \times 2\pi r = x\,m/s$$
$$1.876172608 \times 2\pi \times 22 \times 10^{-3} = 0.6911503838m/s$$
$$= 0.259343483m/s$$
$$= 0.26m/s$$

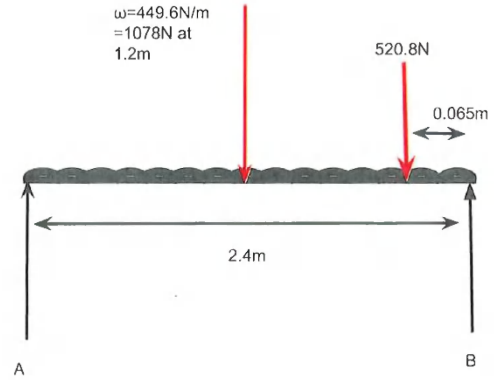
Whilst below the maximum speed this value is still useful as it will allow for the climber to have enough climbing time i.e., the climber will not be rushed. Also, this speed is consistent with the the total height of the wall and will not be too slow or fast to handle, giving the climber a comfortable speed to work with while remaining broadly central on the wall itself as the belt rotates.

Bending Moment at Max Load

I decided to analyse the bending moment calculations when the wall was at max load to best understand the largest forces that will affect the wall.

I show my beam design in the diagram below. The design uses the climber's maximum weight as a universally distributed load (UDL) because the climber's weight would realistically be spread out over the whole wall instead of being situated at just one position along the beam.

Alongside this there is a 520.8N force that accounts for the 6kg motor that will also need to be supported in the system. This forces is calculated using $w = mg \Rightarrow w = 6 \times 9.8 = 520.8N$.

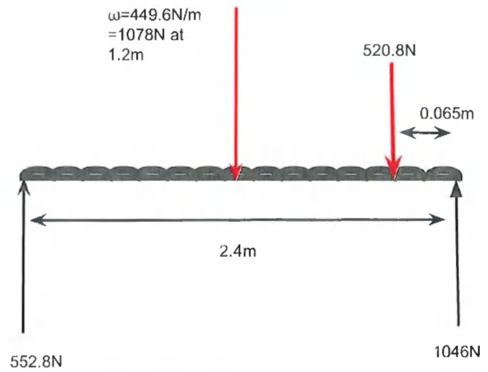


With this diagram it is possible to calculate the reactionary forces A and B by using clockwise and anti clockwise moments, where Σcwm is the sum of the clockwise moments and $\Sigma acwm$ is the sum of the anticlockwise moments:

$When\ taking\ moments\ around\ A$
$\Sigma cwm = \Sigma acwm$
$(1078 \times 1.2) + (520.8 \times 2.335) = (B \times 2.4)$
$2509.668 = 2.4B$
$B = 1045.685N$
$B = 1046N$

$\therefore as\ the\ total\ sum\ of\ upward\ force\ (\Sigma F \uparrow) = \ total\ sum\ of\ downward\ force (\Sigma F \downarrow)$

$\Sigma F \uparrow = \Sigma F \downarrow$
$A + 1046 = 1078 + 520.8$
$A = 552.8N$

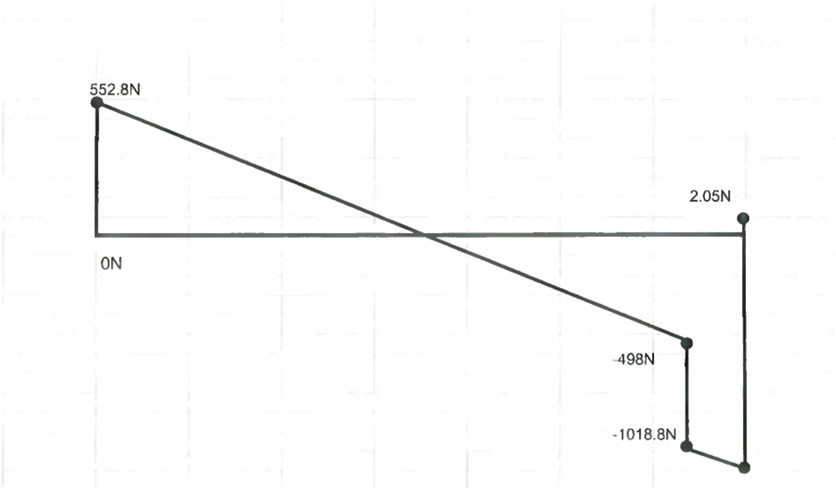


Shear Force Diagram

With these forces calculated a shear force diagram can be made using the above diagram

Point 1: $552.8 - (450 \times 2.335) =- 489N$
Point 2: $- 489 - 520.8 =- 1018.8$
Point 3: $- 1018.8 - (450 \times 0.065) =- 1048.05$
Point 4: $- 1048.5 + 1046 =- 2.05N$

These points allow for a shear force diagram to be plotted. In reality the final point should = $0N$. However due to the rounding of values throughout the process this leads to a small error. This error approximates to $2N$ which is considered negligible.



The shear force diagram is incredibly helpful as it indicates where the maximum bending moment may occur and can be referred to when making a bending moment diagram. As mentioned earlier my calculations show a positive force at the end of the beam. This implies either a direct calculation error or more likely a rounding error. Again, the error is considered negligible as it is a very small percentage of the main forces that are actually affecting the system.

Bending Moment Diagram

To calculate the bending moment (BM) and then make a bending moment diagram from said calculations, a function of the bending moment needs to be created. This is done by considering the beam diagram from above.

Using this information it can be shown that, when x is the position in metres (m), and when $0 < x < 2.335$ the bending moment equation is:

$$BM = 552.8x - \frac{445x^2}{2}$$

This is because the BM for a force is $BM = F \times x$ and for a UDL $BM = \frac{\omega x^2}{2}$

This means a set of points for the first 2.335m can be acquired using this function. This should give a shape representing a parabola with a maximum bending moment which returns to 0N at the end of the beam

$$When\ x = 0.2\ BM = 552.8(0.2) - \frac{445(0.2)^2}{2} = 101.66Nm$$

$$When\ x = 0.4\ BM = 552.8(0.4) - \frac{445(0.4)^2}{2} = 185.52Nm$$

$$When\ x = 0.6\ BM = 552.8(0.6) - \frac{445(0.6)^2}{2} = 251.58Nm$$

$$When\ x = 0.8\ BM = 552.8(0.8) - \frac{445(0.8)^2}{2} = 298.56Nm$$

$$When\ x = 1\ BM = 552.8(1) - \frac{445(1)^2}{2} = 328.3Nm$$

$$When\ x = 1.2\ BM = 552.8(1.2) - \frac{445(1.2)^2}{2} = 340.08Nm$$

$$When\ x = 1.4\ BM = 552.8(1.4) - \frac{445(1.4)^2}{2} = 333.9Nm$$

$$When\ x = 1.6\ BM = 552.8(1.6) - \frac{445(1.6)^2}{2} = 308.76Nm$$

$$When\ x = 1.8\ BM = 552.8(1.8) - \frac{445(1.8)^2}{2} = 267.66Nm$$

$$When\ x = 2\ BM = 552.8(2) - \frac{445(2)^2}{2} = 207.6Nm$$

$$When\ x = 2.2\ BM = 552.8(22) - \frac{445(2.2)^2}{2} = 129.56Nm$$

This set of points allow for the first part of the BM graph to be created. The data shows a steady rise then fall of BM as the distance increases. This means that the equation works as it will create a parabolic shape with a maximum point.

There is still one point needing to be plotted for when $x = 2.335m$, where the motor is located. To do this another equation is needed to account for the force of the motor.

$$BM = 552.8x - \frac{445x^2}{2} - 520.8(x - 2.335)$$

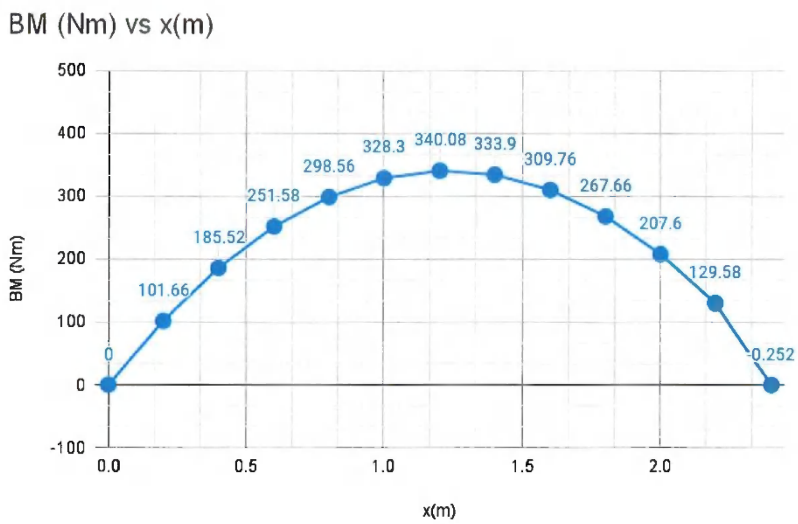
The "$(x - 2.335)$" is used so that the BM for the motor will be calculated correctly as its force is 2.335m from the start of the beam.

Therefore,

$$When\, x = 2.4\, BM = 552.8(2.4) - \frac{445(2.4)^2}{2} - 520.8(2.4 - 2.335) = -0.252Nm$$

In theory this force should = 0. However there is a small force which indicates an error which is due to rounding of decimal places to certain significant figures throughout the process. That said this force is insignificant and is small in magnitude, and this force will also be counteracted by the rest of the frame when the final model is simulated.

Using the above values a BM graph can be made in microsoft excel:



With this graph it is clear to see a definite maximum BM in the beam. This means that the forces acting on the beam are most present around 1.2-1.4 metres. However, the specific maximum BM can be found using mathematical differentiation:

$$BM = 552.8x - \frac{445x^2}{2}$$

This equation is used as the maximum is clearly situated before 2.335m (where the motor is located).

To find the max BM we need to find its distance along the beam - and that occurs when $\frac{dBm}{dx} = 0$ where $\frac{dBm}{dx}$ is the differential of the BM equation:

$$BM = 552.8x - \frac{445x^2}{2}$$
$$dBM = (552.8x - \frac{445x^2}{2})dx = 0$$
$$\frac{dBM}{dx} = 552.8 - 445x = 0$$
$$552.8 = 445x$$
$$x = 1.247727191$$
$$x = 1.25m$$

As we now know where on the beam the maximum BM occurs we can substitute x= 1.25 into the earlier equation to see what the actual maximum BM will be. This value should be less than that highlighted in the specifications (see previous section 1.4 '*The maximum bending moment of the top beam should not exceed 400 Nm*')

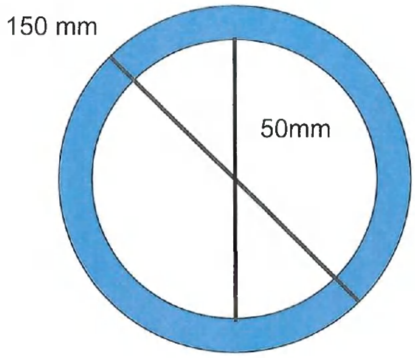
$$BM = 552.8x - \frac{445x^2}{2}$$
$$BM = 552.8(1.25) - \frac{445(1.25)^2}{2}$$
$$BM = 343.34375\ Nm$$
$$BM = 343\ Nm$$

My calculations show that the maximum resistance to bending within the beam is 343 Nm. This is a good result as it abides by the specifications described earlier (1.4) and is less than 400 Nm.

To evaluate: the process of acquiring the bending moment graph and maximum bending moment has been effective as it works within specifications. However there are slight errors caused by rounding These inaccuracies are considered immaterial, and it is anticipated they would be easily countered when the model is fully simulated and/or constructed. My analysis also shows that the beam on the top of the wall will not bend easily, if at all under the forces likely to be applied, which is useful to know. The beam also works within the specifications (see 1.2 and 5.5) and it can therefore be assumed that the specifications outlined are relevant and will work when the final design is made.

Second Moment of Area and Maximum Deflection

By calculating the second moment of area it will describe the beam's resistance to bending due to its shape and surface area. As the beam is hollow the value will be slightly less than a solid beam - but calculations can be done to still determine if it will be a usable beam assuming a certain wall thickness.



The equation for second moment of area (I) is

$$I = \frac{\pi d^4}{64} - \frac{\pi (d_2)^4}{64}$$
$$I = \frac{\pi * 150^4}{64} - \frac{\pi * 50^4}{64}$$
$$I = 24543692.61 mm^4$$
$$I = 25 \times 10^6 mm^4$$

This value for the second moment of area is viable as it is not exponentially larger than other values previously calculated and it also correlates to the BM equations earlier which shows that the beam will not bend easily as there is a lot of resistance to bending within this beam. The second moment of area calculations also confirms this. The calculations are supportive for the project as they agree with the specifications (5.1).

Using this value we can also calculate the bending stress of the beam. This value must be less than 2 Nmm^{-2} as quoted in the specifications (seen 5.5).

To do this the general bending moment equation is used:

$$\frac{M}{I} = \frac{E}{R} = \frac{\theta}{y}$$

Where M is the bending moment, I is second moment of area, θ is the maximum deflection and y is the distance between neutral axis and tension edge.

As the max bending moment has already been calculated previously (343 Nm).

$$\frac{M}{I} = \frac{\theta}{y}$$

$$\frac{343}{24543692.61} = \frac{\theta}{75}$$

$$\theta = 0.010481306$$

$$\theta = 0.01Nmm^{-2}$$

This figure links directly to my specifications (see 5.5) and it should be noted that 0.1 Nmm^{-2} is significantly smaller than 2 Nmm^{-2} as previously specified. This shows that the specifications previously stated were effective. The calculations also show that even with all the assumed forces acting on the beam it will not be allowed to bend.

Again using values from above, the value of Young's modulus can be calculated through the maximum deflection. As the specifications state that stainless steel should be used, the value for Young's modulus should be close to $196KNmm^{-2}$ however if this value is exceeded then this specification will need to be changed (i.e. a different material should be considered):

$$\delta = \frac{Ml^2}{12EI}$$

$$E = \frac{343*2400^2}{12*2.5*10^3*25*10^6}$$

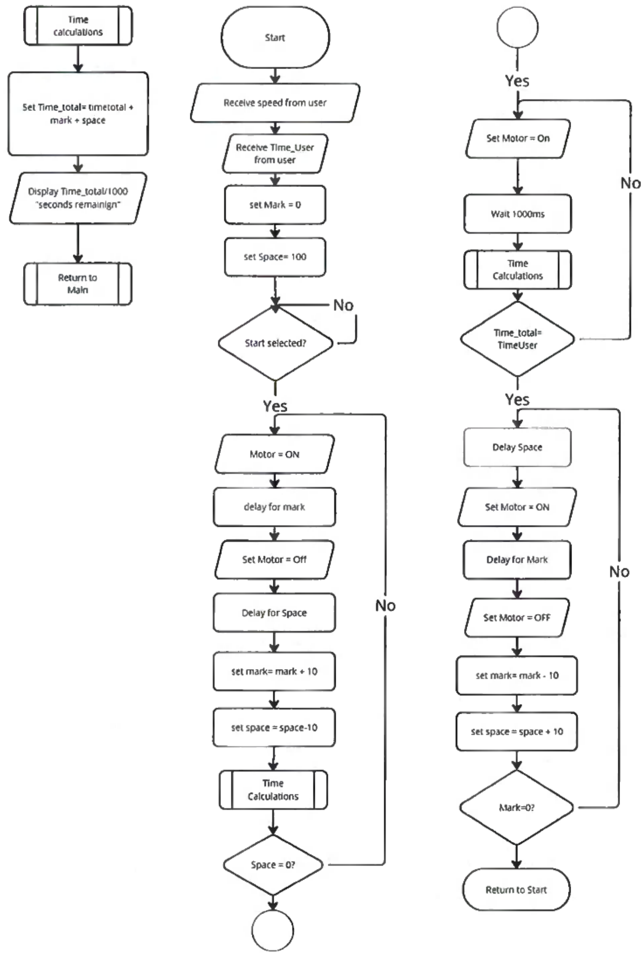
$$E = 1.0976Knmm^{-2}$$

This value is significantly smaller than $196KNmm^{-2}$. Therefore, a beam as designed and made of stainless steel would be safe to use as a roller for the top beam. Indeed such a beam is unlikely to see any yield stress or strain that would cause any bending or deformation to occur.

Electronic Modelling

Flowchart

To start my electronic modelling for this project I first considered the programming for my system. I decided to use a flowchart to look at how the motor would use a soft start and to support calculations for the time that is displayed for the timer. The flowcharts clearly show how each part of the system operates.



The flowcharts clearly show the processes needed in the system and how they will interact with one another at each stage of the process. The flowcharts also demonstrate one way of creating pulse width modulation (PWM) in the system by coding (and support an easy way to incorporate into the program).

555 Timer

A 555 timer will be used in my system as a way of alerting any third party observers to whether the treadmill is being used or not. This will be done by sending supply voltage through the circuit as the belt is switched on and powered up. The 555 timer will be connected to an LED that will flash with a frequency of 0.01Hz which means that there will be one oscillation per second. This means that the mark and space time should add up to equal 1 second.

To do this $T_1(mark\ time) = 750ms$ and $T_2(space\ time) = 250ms$ therefore as a $1\mu F$capacitor will be used in this circuit and because $T_1 + T_2 = 750 + 250 = 1000ms = 1s$, the period of oscillation will be 1 second as stated in the project specifications (see 4.5).

This means that because;

$T_1 = 0.7(R_1 + R_2)C$

And as

$T_2 = 0.7R_2C$

$\Rightarrow T_2 = 0.250 = 0.7 \times R_2 \times 1 \times 10^{-6}$

$R_2 = \frac{0.250}{0.7*1*10^{-6}}$

$R_2 = 357142.8571\Omega$

$R_2 = 357K\Omega$

This means that R_1 can be calculated as follow;

$R_1 = 0.7(R_1 + R_2)C$

$0.750 = 0.7(R_1 + 357000)1 \times 10^{-6}$

$R_1 = (\frac{0.750}{0.7\times1\times10^{-6}}) - 357000$

$R_1 = 714288.7145\Omega$

$R_1 = 714K\Omega$

These calculations allow the circuit to be simulated. We can also determine if the calculation of the resistor values is correct.

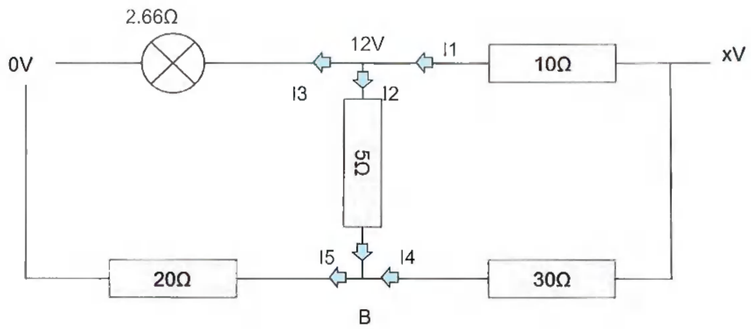
The analysis shows that a high resistance circuit will be needed. On that basis, it will be suitable for most supply voltages that would realistically be implemented on the wall such as 12V supply.

When simulated, the output voltage will be determined alongside the frequency of current and voltage in the system. This model also shows that using a 1 second time period is supported. This period is considered long enough for the flash to be noticeable and visible without being distracting for the climber, allowing for this system to be mainly used by third parties that are either observing or are located near the treadmill when it is active.

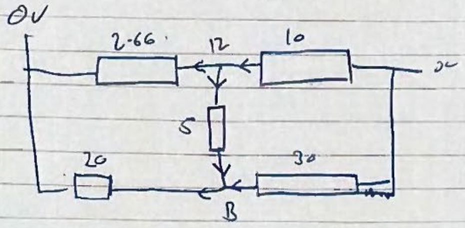
While it would be hard to source such specific values of resistors it is possible to use multiple resistors. For example, for the 714KΩ resistor the sum of: a 470KΩ, a 220KΩ and a 20KΩ resistor can be used (total 710KΩ) which is slightly lower than calculated. While this will impact the time delay the difference will be materially insignificant, and each flash period will still be very close to 1 second. In a similar way, it is also possible to use multiple specific resistors to arrive at a total resistance close to the 357KΩ resistor that is required in the circuit outlined above.

Nodal Analysis

An optimal output from the motor of 12V is needed as that is what the motor is rated for (see DC Geared Motor). This means that a supply voltage will need to be calculated using electrical nodal analysis. An input and other nodes can be calculated to see the magnitude of voltage at each node, assuming various resistors are used that are reasonably sized in comparison to the internal resistance of the motor. These sizes could be changed to mimic the other components of the circuit after further development. To start, using smaller sizes ranging from 5-30Ω would be useful to help with calculations and design when it comes to building and simulating this circuit in the first instance.



The diagram above indicates how Xv can be calculated using Kirchoff's 1st Law which states that the current flowing into a node (or a junction) must be equal to the current flowing out of it. In the diagram, for nodes A (12V) and B (unknown) the sum of the inputs must equal the sum of the outputs. The working below expands on $V = IR \Rightarrow I = \frac{V}{R}$ and uses Kirchoff's law to calculate Xv:



$I_1 = I_2 + I_3$

$$\frac{x - 12}{10} = \frac{12}{2.66} + \frac{12 - B}{5}$$

$$13.3x - 159.6 = 600 + 319.2 - 26.6B$$

$$x = \frac{1078.8 - 26.6B}{13.3}$$

$I_4 + I_2 = I_5$

$$\frac{x - B}{30} + \frac{12 - B}{5} = \frac{B}{20}$$

$$100x - 100B + 7200 - 600B = 150B$$

$$100x + 7200 = 850B$$

$$100\left(\frac{1078.8 - 26.6B}{13.3}\right) = 850B - 7200$$

$$107880 - 2660B = 11305B - 95760$$

$$203640 = 13965B$$

$$B \approx 14.58 \checkmark$$

$$\therefore x = \frac{1078.8 - 26.6B}{13.3}$$

$$x \approx 51.95279195$$

$$\approx 52V$$

The working above shows that there must be a supply voltage of 52V to the motor for it to function at full capacity with the resistor values chosen. A relay could also be used to isolate this circuit gaining more control over the voltage regulation. This is effective as it gives a precise value that the motor can efficiently work at to power the climbing wall. The value realised is also reliable as B is proportional to A and for the resistor values used, it makes sense to have a higher input voltage. I also chose to use these resistor values as they are standard resistors meaning that they are easy to source and obtain.

This circuit can now be designed and tested to determine whether the maths was correct and to show if an input of 52V is indeed needed.

Constructing and/or simulating a solution

Simulations

Structure Simulations

Main Structure Model

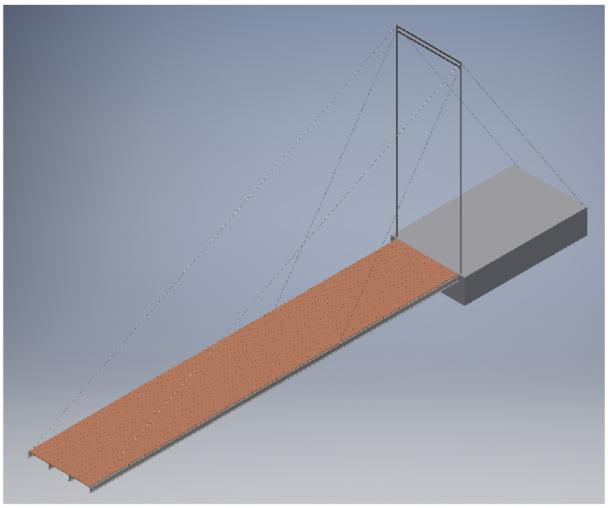


Figure 3: Model of main bridge structure

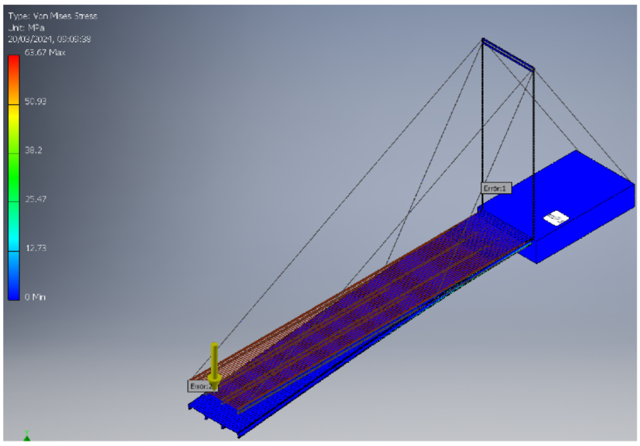


Figure 4: Stress analysis of bridge structure model

The purpose of the 3D model in Figure 3 and Figure 4 is to show the integration between all of the different components of the structure and perform a stress analysis and test how the bridge would react under stress in a real world situation. The dimensions of the different components were all calculated during the structure calculations part of this project.

I received assistance from my teacher in order to perform a stress analysis simulation on the model and the results are shown in Figure 4. The expected results from the stress analysis were a slight bend at the end of the bridge with larger stresses in the I beams at the start of the bridge and low stress in the deck planks. The actual results match the expected results but were not perfect due to the limitations of the software preventing an accurate UDL from being tested and some of the cables not being detected when performing the stress analysis.

Electronics Simulations

Control System Flowchart

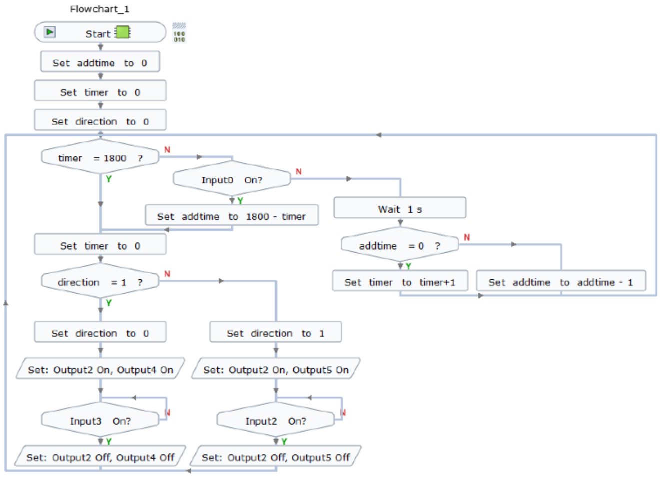


Figure 5: Non annotated control system flowchart

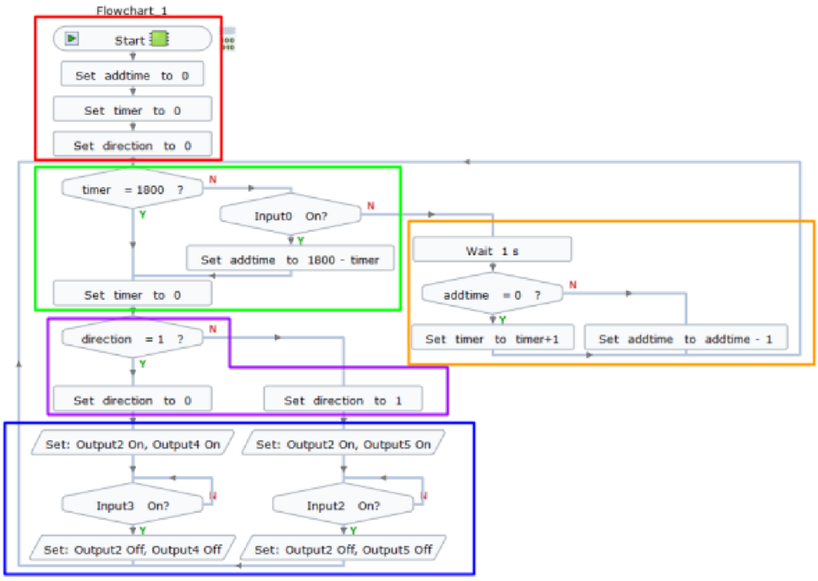


Figure 6: Annotated control system flowchart

The purpose of the flowchart shown in Figure 5 and Figure 6 is to control when the motor turns on and off and what direction the motor will rotate.

The red section of Figure 6 is used to create the variables to be used later in the flowchart and assign initial values of 0 to each. The addtime variable is used to track any additional time to the next bridge fold or unfold due to a manual override causing the bridge to change position early. The timer variable is used to track the time since the last time the bridge moved. The direction variable is used to track what direction the motor will rotate in.

The green section of Figure 6 is used to check if the motor should be turned on by checking if the timer has reached 30 minutes or if the manual override has been pressed. If the timer reaches 30 minutes then the timer will be reset to 0. If the manual override is pressed then the remaining time on the timer will be stored in the addtime variable and the timer will be reset to 0.

The orange section of Figure 6 is used to reduce the addtime and timer variables once every second. If the addtime variable is not equal to 0 then it will be reduced by 1 and the timer variable will remain the same. If the addtime variable is equal to 0 then the timer variable will be reduced by 1.

The purple section of Figure 6 is used to check which direction the motor should rotate in. The direction of the previous rotation is checked and then inverted.

The blue section of Figure 6 is used to control the motor by using two different outputs to control direction and limit switches at two different inputs to control when the motor turns off. The left side is used to control the anticlockwise rotation of the motor while the right side is used to control the clockwise rotation of the motor. Once the motor is turned off the flowchart loops back to repeat.

The expected result when the flowchart was tested was for the motor to turn on after 30 minutes or when the manual override was pressed and would rotate in alternating directions each time it was turned on. The flowchart was also tested to ensure that the additional time was correctly added on if the manual override was and the motor would only turn off once the correct limit switch was activated. The actual results did not initially match the expected results as the timer section shown in orange in Figure 6 was not correctly created so it was fixed and then the flowchart worked correctly.

Control System Circuit

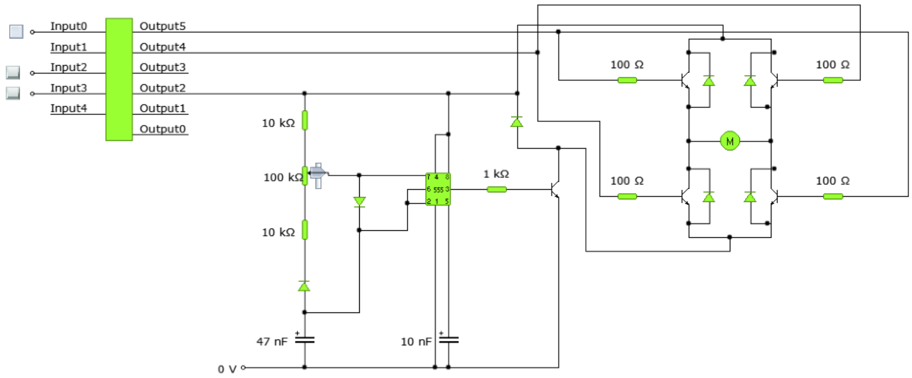


Figure 7: Non Annotated Control System Circuit

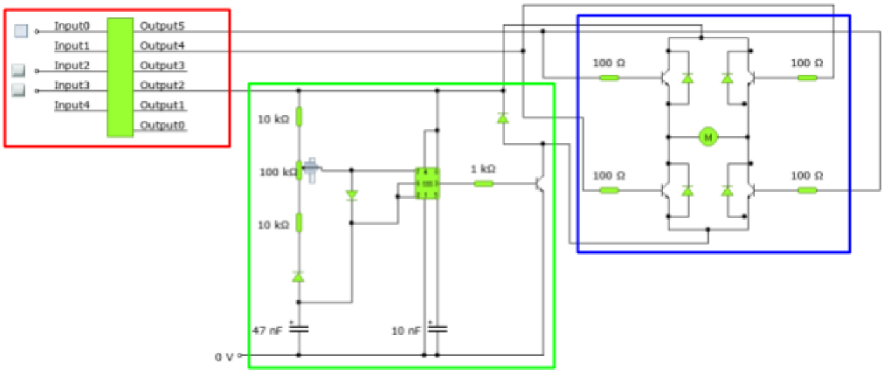


Figure 8: Annotated Control System Circuit

The purpose of the circuit shown in Figure 7 and Figure 8 is to control the speed and direction of the motor using the inputs and outputs from the microcontroller.

The red section of Figure 8 shows the microcontroller linked to the previously shown flowchart from Figure 5 and Figure 6 with with Input0 as the manual override button, Input2 as the clockwise limit switch, Input3 as the anticlockwise limit switch, Output2 linked to the 555 timer and motor, Output4 connected to the anticlockwise transistors of the H-bridge, Output5 connected to the clockwise transistors of the H-bridge.

The green section of Figure 8 is the Astable 555 Oscillator used to control the speed of the motor with a PWM signal as shown in the pulse width modulation research section of this project. The potentiometer is set to have a top half resistance of approximately 41kΩ and a bottom half resistance of approximately 59kΩ to create the required PWM signal.

The blue section of Figure 8 is a transistor H-bridge used to control the direction of rotation of the motor by saturating two transistors. The design of the transistor H-bridge came from (Mafukidze, no date) The top right and bottom left transistors are connected to Output4 to allow the motor to rotate anticlockwise while the top left and bottom right transistors are connected to Output5 to allow the motor to rotate clockwise.

The expected result when the circuit was tested was for the motor to turn at 41% of its standard speed and would rotate in different directions based on which output was on. The actual result matches the expected result but did not match the calculated values due to the limitations of the software the exact values of the potentiometer and motor speed but the potentiometer was set to an approximate match and the motor was tested with the default speed that the software used.

Evaluation

Reflection on Implementation

Throughout the implementation stage of this project I have faced some challenges and had to make some changes. By far the biggest challenge I have faced is time management. I have found myself straying wildly from the project plan and missing target dates for when I wanted to get tasks done for. For example, I think I took far to long working on the electronics of the control system which meant I had less time for the hull and propulsion subsystems of the ROV. Throughout the implementation stage I have also learned many new skills. For example, I have learned how printed circuit boards are designed and constructed. I have also learned how to use Kicad which is a software package used to design printed circuit boards and electronics, this is a skill I think will come in extremely handy in future going into further education and the working world. There are some areas of the implementation of the ROV which I would like to have refined further however if I had more time. For example I would like to have further improved the shore controller, I am not entirely happy with the method of input and control and would like to have spent more time refining this to allow for easier more seamless operation of the ROV, however as already mentioned I had already spent far to much time developing the control systems so any additional time on top of that working on the shore controller would have been to the detriment of the quality of the rest of the ROV. Another aspect of the implementation of the ROV which I would like to have improved upon if I had more time was coming up with a better solution for the adapter piece between the main body tube and the camera dome. I am unhappy with the fact that it would have to be 3D printed, as I found out in the research section that it was unwise to have structural and waterproof parts be 3D printed. The only other alternatives I could think of for this part involved machining metal which goes against the initial goal of reducing cost, however with some additional time to think I could likely have come up with a better solution. I am particularly happy with how the propulsion system turned out. I think my design for the magnetically coupled thruster is a good solution which allows relatively low cost components such as brushed DC motors (as opposed to more expensive brushless motors which require speed controllers) to be constructed into a thruster which can be used underwater, however as with the entire rest of the ROV it would ideally need to be physically constructed to fully test and refine the design.

Evaluation of solution

As we come to the conclusion of this project it is important to evaluate the solution. The initial aim of this project was to "broaden accessibility to underwater surveillance by creating a low cost remotely operated underwater vehicle", the key words there being that the ROV should be designed to be constructed, operated, and maintained for a low as possible cost and that it should provide "underwater surveillance capabilities" in other words it should provide video output.

First let us discuss the cost. In terms of the materials used, the main construction materials are PVC and PLA. PVC as already discussed is widely used in plumbing and gardening, especially in pipe form which is handy for this project. The fact that it is widely commercially available means that it can be easily obtained from most construction retailers as well as there being many outlets on the internet. This means that it can be found for a low price which reduces the cost of the ROV. The fact it is easily obtained also means that replacement parts can be sourced without difficulty extending the operating life of the ROV and therefore saving the potentially large cost of buying a new one. The fact that PVC is commonly found in pipe form which is the shape it is used in the ROV means that the cost of fabrication is also reduced. Because PVC is used in plumbing it is also made to be watertight and corrosion resistant which is also a plus. PLA is a plastic which is used in FDM 3D printing. The main advantages of PLA are that it is relatively simple to work with compared to other materials such as resins used in 3D printing and that it is one of the more commonly used 3D printing materials therefore it is cheaper. The FDM 3D printers used with PLA also tend to be cheaper, more accessible, and more widely available than other types of 3D printing (Leapfrog, 2020) therefore reducing cost. 3D printing has the major advantage that it allows complex shapes to be easily manufactured therefore reducing cost as other forms of manufacturing complex shapes such as injection moulding may take longer and be greatly more expensive as well as requiring expensive moulds to be made. 3D printing also reduces cost by allowing flexibility. For example, if a part is not functioning properly or is broken another one can be easily redesigned and re-printed. This extends the operating life of the ROV and therefore reduces cost. Overall, the material choices were successful as discussed effectively allowing the cost to be reduced. As touched on earlier the ROV was also designed to make use of "off the shelf" components, for example the electronics were designed so that they would be compatible with most analogue security cameras, this provides options and therefore reduces the cost.

The ROV fully meets the aim of providing underwater surveillance capabilities. It does this by incorporating a camera in the front of the ROV with a clear view to survey out through the front camera dome. The output from the camera is sent via the onboard controller, up the tether and to the shore controller, which is with the operator, were an output port is given which can be plugged into a monitor or similar device to view the video from the camera. This allows the operator to visually survey marine environments and therefore successfully meets the aim of providing underwater surveillance capabilities.

So how does this ROV compare with other ROV's in its category in terms of price? To finally answer the question of how much the ROV would cost to construct prices were obtained for all materials and components used. After some calculation a final unit price of £161.00 was obtained a full breakdown of the price of components can be found in the table below. Prices were found on manufacturers and supplier's websites such as SnapEDA (SnapMagic, 2024).

Part	Price	Quantity
RJ45 Socket	$2.68	2
SP3T Switch	$0.49	3

Video balun and BNC connector	$6.00	2
555 timer	$0.77	1
Battery holder	$1.03	2
resistor	$0.03	4
capacitor	$0.02	1
Variable resistor	$0.58	1
PCBs	$2.00	2
DC barrel jack	$0.67	1
LED	$0.26	2
SPST Switch	$1.85	2
MOSFET	$0.18	12
Camera	$21.55	1
XT60 Connector	$0.38	1
Lipo battery	$31.99	1
DC motor	$12.99	3
Magnets (multipack)	$7.99	1
Ball bearings (multipack)	$10.98	1
PVC body tube	$12.85	1
End Cap	$1.48	1
Camera dome	$13.99	1
O-ring	$7.41	1
Threaded inserts	$0.03	4
screws	$0.08	4
PLA 1kg Spool	$13.99	2

Some research was done into other ROVs which provide visual surveillance at relatively shallow depths. During the summer I attended a lecture from some robot researchers from Edinburgh who when questioned recommended I look into ROVs from Blue Robotics. Blue Robotics sells parts for ROVs and also sell their own ROVs one of these models is the “BlueROV2” which they claim is “the world's most affordable high-performance ROV” (BlueRobotics, 2024) this ROV is capable of diving to a depth of 100m which is more than the ROV in this report is designed for but still not extreme depth. The “BlueROV2” also sports an onboard camera and lighting like the ROV in this report. However, the “BlueROV2” also is quoted at a price of $4250.00 (BlueRobotics, 2024) which is over 2000% more than the ROV in this report. Another ROV which provides similar functionality to the one in this report is the “BW Space Pro” from Youcan Robot. The “BW Space Pro” is also able to dive to 100m, has 3 thrusters and a camera, along with some extra functionality like being able to save pictures, but comes at a price of $1299.00 (Youcan Robot, 2017) this is an over 600% increase in price from the ROV in this report. In fact, I was unable to find any comparable ROVs for less than £320. This means that in terms of keeping material costs to a minimum this project has also been extremely successful. This along with the built-in maintainability leads me to the conclusion that the ROV is verry successful in fulfilling the aim of broadening accessibility to underwater surveillance by creating a low-cost underwater vehicle.

Subsystem	**Evaluation**	**Further Developments**
Main hull	As already discussed, in terms of meeting the aim of reducing cost the main hull was quite successful. The materials used (PVC and PLA) provided a good balance of strength	I would like to have come up with a better solution for the adapter piece between the main body tube and the camera dome. It is not ideal having the

	corrosion resistance, while also being cheap and readily available. The shape of the main hull drew from conclusions of other research papers to create a design which was both pressure resistant and hydrodynamic. The hull also is successful in reducing cost by making use of already existing, commercially available components such as using spare parts for a security camera as a camera dome. This cuts out potentially complex fabrication and therefore reduces cost directly achieving the main aim of widening accessibility by reducing cost.	adapter piece be 3D printed, as we found in the research section this could cause leakage. However, I was unable to come up with a better solution in the given time which did not involve complex and expensive machining. If I were to further develop this however, I feel that I would be able to come up with a more optimal solution which is cheap and does not introduce the structural problems of SLA 3D printing. An alternative solution may include finding commercially available components made out of PVC or similar which could do the job or finding an alternative accessible and cheap fabrication method which produces strong, watertight parts.
Variable buoyancy system	Calling it a variable buoyancy system is a bit of a misnomer as it is not truly variable during operation. The variable buoyancy system allows the buoyancy of the ROV to be adjusted and set prior to operation by loading and adjusting the ballast compartments. It was concluded in the research section of this report that having a buoyancy system which could be actively varied during operation would add too much cost and complexity, which directly goes against the main aim of this project. For the application of providing underwater surveillance however the implemented buoyancy system is all that is needed as the ROV is unlikely to encounter situations where it would dynamically require more or less buoyancy for example picking up objects. The implemented system is both extremely simple and easily maintained, therefore it is extremely unlikely to fail and is inexpensive, which directly fulfils the aim of this project.	Future developments of the variable buoyancy system could include constructing a physical version of it and performing tests to confirm the calculated values of ballast required. Tests could include testing whether it can achieve neutral buoyancy and testing if it is able to trim the ROV so that it floats in the correct orientation. Outcomes of tests may suggest further improvements to the system like adding more compartments for finer control of weight distribution or allocating more space for additional ballast. It is important that the buoyancy system is fully refined. This is because a poorly designed buoyancy system could render the ROV entirely uncontrollable and inoperable by causing it to have to much buoyancy and therefore not being able to dive or having to little buoyancy and sinking of being unevenly

		ballasted and floating at an angle making movement and navigation difficult.
Control system	The control system encompasses the onboard and shore controllers as well as the camera and tether. The shore controller takes inputs from the operator and sends them down the tether to the onboard controller which processes them and carries them out. The control system provides three states for each of the motors forwards, neutral, and reverse as well providing a degree universal speed adjustment. To evaluate the control system, I think it is successful in creating a simple low cost solution however it does not provide very precise control of the ROV's movements the way speed adjustment of each individual motor would. The camera system is an aspect of the control systems which is quite successful. The way it has been designed allows it to be compatible with many commercially available analogue security camera systems this increases the accessibility and reduces cost which directly meets the initial aims of this project.	Future developments of the control system would hopefully include finer control of the motors and include an easier input method than slider switches. This could be achieved for example by allowing the speed of each motor to be controlled by a variable resistor attached to a lever, or some form of mixing could be done with the electronics to allow for joystick input to control the ROV, this would provide much greater and more precise control of the ROV. This however would take significant extra development time to create a solution which still maintains a low cost. In future it would also be good if a housing for the shore controller could be designed instead of just having the bare PCB. A housing for the shore controller would provide a more comfortable experience for the operator as well as providing protection for the PCB, therefore increasing its lifespan, and reducing cost. The housing could be 3D printed as it does not need to be watertight or pressure resistant.
Propulsion system	The propulsion system comprises of the two horizontal and one vertical thruster. It was found in the research section of this report that DC motors are able to somewhat withstand being submerged however it was also concluded that it would be advantageous to also make use of a magnetically coupled thruster design for extra protection. The main construction of the thrusters is made from 3D printed parts, which offers a cheap solution to fabrication of complex parts. Overall, the thruster	It is somewhat unclear just from the design how effective at transmitting rotational movement the magnetic coupling system would be. A useful further development, as with the variable buoyancy system would be to conduct tests with a physically constructed version of it. A thruster could be built, and it could be tested how much torque it is able to provide as well as testing how much thrust

	provides a design which is cheap, easily produced and makes use of easily obtained, commercially available components. This directly meets the initial aims of this project.	it gives when submerged in water. The results of the tests could then be used to further refine the design of the thrusters. For example, if it is found that the magnetic coupling system in ineffectively transmitting rotation more magnets could be added, or the rings of magnets could be moved closer together.

Evaluation of process

The development of this report has had its ups and its downs. An area of the development which I am quite proud of is the research section. As I mentioned on the 15/11/23 in my record of progress there was a lot of things that I did not know that I did not know, and therefore hadn't considered to research, though through my initial sources I was made aware of more and more which took me down many rabbit holes of research. One area where I kept discovering more and more was when researching the communication between the ROV and the operator. I initially was only trying to find information on underwater radio communication however as I did this research, I also found out about underwater light and audio communication, so I therefore did some research on this as well. Going down these many branching paths of research led me to gather lots of interesting and useful information and led to a research section which I feel is of a quite high quality.

Doing such extensive research however also came at the expense of my time management. As we can see from the log of progress my research took many months (15/11/23 – 25/2/24) while initially in the project plan, I had only aimed to spend about a month on it (see Figure 9 Gantt chart. Version 1.1.). In reviewed versions of the project plan I did end up trying to allocate more time to it (see Figure 12 Gantt chart further updated. Version 1.4.) however I ended up overrunning these timings as well. Because of this I had less time for the later tasks such as the implementation stage where I feel I could have done with some extra time to provide fuller explanations of all my design decisions and components. I have now realised and learned how important it is to strictly stick to the project plan. I have learned that while it may in the start seem like it is fine to take it easy at the start, in the long run it is much simpler to stick to the project plan as it causes less stress towards the end of the project.

Throughout the project as I mentioned in an entry in the progress log on 15/2/24 I have been finding it easier and easier to write texts. Initially at the onset of this project I would say I was quite hopeless at writing paragraphs of text. I found it difficult to get my thoughts into cohesive words and found that it was tricky and get my sentences to flow. However, throughout the project there has been many opportunities to practice my writing skills and now the project is drawing close to its conclusion I am finding it somewhat easy to just sit down and get my thoughts onto the page. I am also finding that my writing flows better and is less disjointed.

A new skill I have acquired through writing this project is formal referencing, in this case I decided to use the Harvard referencing system. I have learned how it is done and where it should be used. Formal referencing is something which was completely foreign to me starting out on this project but now nearing its conclusion I feel relatively confidant in my referencing abilities. Formal referencing is a skill which will come in extremely useful going forward into university and the workplace.

An area of the development which I think could have been done a bit differently is my mathematical modelling and analysis section. I think I could have done a bit more mathematical modelling before diving into the implementation of the solution. The way it was done was that I ended up doing the mathematical modelling somewhat in parallel with the start of the implementation which meant I ended up checking if things could withstand the required forces after the fact. This led to situations where components ended up being massively over engineered for what turned out to be relatively little force on them. An example of this is the horizontal motor mount in which it was calculated that its members would experience a maximum stress of $0.024Nmm^{-2}$ whereas the maximum force the member could theoretically withstand was way up at $60Nmm^{-2}$. In reality, reducing the material used in the members would likely equate to negligible savings due to their already small scale and it would have pushed the accuracy of the 3D printer used. However, in principle it would have been better practice to comprehensively mathematically model everything first then design components with a factor of safety based around the calculated values. This would also have led to a better structured report.

In future I would take extra care creating the project plan. I now have more experience to base my projected timings on so could divide the time more effectively between tasks that I now more accurately know how long take. I would then be able to manage my time more effectively and put in more effort to rigidly stick to the project plan, reducing stress and increasing the quality of the project overall. I would also continue to refine the project text with my new found writing skills, re writing parts to make them clearer, and adding more detail where necessary.