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Consumer Oriented Remotely Operated Underwater Vehicle

Tavakasutajale mõeldud mehitamata allveesõiduk

MSc thesis

The author applies for
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AUTHOR'S DECLARATION

I declare that I have written this graduation thesis independently.

These materials have not been submitted for any academic degree.

All the works of other authors used in this thesis have been referenced.

The thesis was completed under Priit Põdra's supervision

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The thesis complies with the requirements for graduation theses.

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Accepted for defence.

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TUT Department of Mechatronics
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MSc THESIS TASK

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Student: Ott Õismaa 143860
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No.	**Description of the assignment**	**Completion date**
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2.	Market analysis.	**25.03.16**
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4.	Mechanical design of the prototype.	**06.05.16**
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Engineering and economic problems to be solved: The main task is to develop the conceptual design of a consumer oriented ROV which could be used in the future as a basis for creating an actual prototype that would be competitive on the market.

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Student Ott Õismaa /signature/ ………. date………

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EESSÕNA

Käesoleva töö teema tuleneb autori isiklikust huvist erinevate mehitamata sõidukite vastu. Autor soovib tänada juhendaja Priit Põdra’t nõuannete eest töö vormistamisel.

1. INTRODUCTION

The aim of this thesis is to develop the design concept of a consumer oriented remotely operated vehicle (CROV) for recreational underwater exploration and/or videography. Key characteristics of the CROV would be portability, affordability and ease of use – all of which have been a lower priority with existing solutions.

Motivation for this topic has come from the author's personal interest and experience with UAVs. The current market situation also shows signs of consumer ROVs becoming a trend in the near future similarly to consumer UAVs a few years back. Therefore it is a suitable time to develop solutions in this field, so they could potentially be used to create real products in the future.

Expected result of this work would be seen as a conceptual design of a CROV. This concept could be used as a basic framework for developing CROV prototypes in the future. The first task is to analyse current trends and existing solutions on the developing market of consumer ROVs. The data gathered in this analysis is subsequently concentrated into a set of design criteria, which should be taken as a reference while designing a CROV. All major technical aspects concerning the design of a CROV are to be identified and discussed in order to provide a comprehensive set of information that could be useful for successfully developing a CROV that meets set criteria. A preliminary mechanical design of a prototype is also to be developed, along with calculations and simulations.

1.1 Purpose

Roughly 70 % of the planet is covered with water, meaning that most territories cannot be accessed by humans without special equipment. So far, the easiest way for one to start exploring the underwater world is to take up scuba diving. Of course, the diver gets to experience the underwater world first-hand, but at a cost of personal safety. While underwater, the well-being of the diver is completely reliant on the equipment used. Even if small depths are considered, anyone who wishes to take up scuba diving has to pass a course in order to do so. Moreover, the risks involved, qualifications required, and the complexity of equipment used grows exponentially with increasing depth. Non-professional, recreational divers cannot go beyond only 50 m of depth.

However CROVs could appeal also to many other interest groups aside from divers. For example, it could be used by marine research scientists, who are on a small budget. They could use CROVs for simple visual inspection tasks or for collecting samples. In principle, CROVs could also be used in the marine industry, as an expendable piece of equipment. For example, in order to do preliminary inspection of high-threat environments, to identify if it is safe to proceed with expensive industrial equipment.

There is likely a number of ordinary people who are fascinated by the marine world but would like to experience it in a more convenient way. Consumer-oriented UAVs have enabled regular people to operate aircraft and experience flight, with small costs and almost no training involved. Consumer ROVs could provide the same opportunity for underwater exploration.

1.2 Background

This subsection will give a brief overview of existing unmanned submersible vehicles, in order to provide better understanding of the further chapters of this thesis.

In general, underwater vehicles are divided into two categories: manned and unmanned underwater vehicles. Unmanned vehicles are further categorized to remotely operated vehicles (ROV) and autonomous unmanned vehicles (AUV). [1]

1.2.1 ROV vs AUV

An ROV differs from an AUV in the most basic sense that an ROV has a wired link (called the tether or umbilical) with its operator, while the AUV is free from cables and runs fully autonomously. Under the constraints of current technology, teleoperation of a submersible that is underwater can only be achieved with a wired link. The reason for this is the fact that radio waves penetrate water very poorly. Although very low frequency radio waves are able to penetrate water farther, the data transmission rates at these frequencies become unacceptable for transmitting real-time video. [1]

AUVs can run either a pre-programmed course or have adaptive mission control. As opposed to the ROV, which is designed to work in a rather confined area, the AUV is able to cover large distances on its own while carrying out its tasks. This introduces a principle difference in hull shape designs of the ROV and AUV. The hull of an AUV is designed to be as hydrodynamic as possible to reduce drag forces applied while travelling through water. Thus, efficiency is improved and the AUV is able to go further. Hydrodynamic design of an ROV has not been a priority, as most existing ROVs are also powered via tether and therefore, in principle, are able to work indefinitely. [1]

As the aim of this work is to develop a tele-operated submersible, only ROVs will be further discussed.

1.2.2 Classifications

ROVs are used for several tasks, where it is either too difficult, dangerous or expensive for the human diver to reach - from inspecting ships' hulls to subsea construction. ROVs can roughly be divided into three main categories based on their size and purpose. The following will briefly describe key characteristics of the different classes.

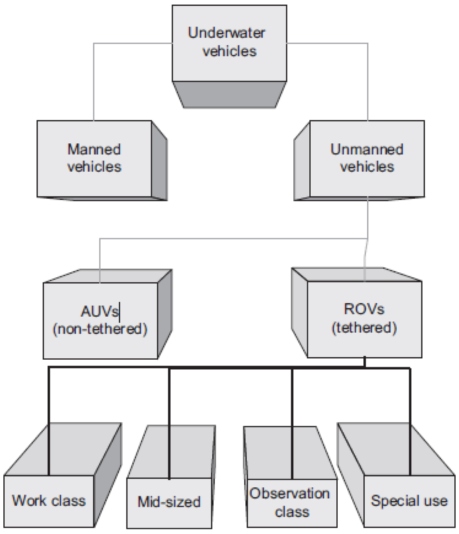

Figure 1.1. Classification of underwater vehicles. [1]

Observation class

Observation class ROVs or OCROVs range from the smallest micro-ROVs up to vehicles weighing 100 kg. As their name implies, OCROVs are used for shallow water (less than 300 m depth) inspection. Due to low required depth ratings and the absence of tooling, the costs of OCROVs can be kept to the lowest. These ROVs are hand-launched and their tether is managed also by hand. [1]

Mid-sized

Mid-sized ROVs (MSROVs) are a step up from OCROVs. MSROVs allow for higher depth ratings, for example, by having more capable pressure housings and equipment for managing the longer lengths of required tether (tether management system or TMS). MSROVs also use electrical power for thrusters and tooling. However they may have some additional hydraulic capabilities in some cases. The mass of these ROVs range from 100 kg up to 1000 kg and therefore need a dedicated system for launching and recovery. [1]

Work class

Work class ROVs (WCROVs) are the heaviest unmanned, tele-operated submersible vehicles, that run on high voltage (>3000 VAC). They use hydraulics for both propulsion and tooling. The WCROV can perform heavier tasks thanks to more powerful manipulators and tooling when compared to MSROVs. [1]

Table 1.1. Typical characteristics of main ROV classes. [1]

Vehicle category	**Depth rating, m**	**Mass, kg**	**Cost, €**	**Power**	**Tether type**	**TMS**	**Thruster type**	**Tooling**
OCROV	300	<100	85000	Low voltage DC	Copper	None	Electric	Electric
MSROV	2000	100...1000	1300000	Medium voltage DC or AC	Copper or optical fibre	Optional	Electric	Electric or hydraulic
WCROV	>3000	>1000	4400000	High voltage AC	Optical fibre	Mandatory	Hydraulic	Hydraulic

1.2.3 Cost of professional solutions

Main reasons for the high cost of most ROVs are as follows.

Depth rating – More exotic materials are needed to cope with the increasing pressure as the vehicle goes deeper under water. Parts have to be precision-machined for the dry compartments of the vehicle to remain resist water at greater depth. [1]

Durability – Due to the high standards and requirements set in the marine industry, maximum durability dependability has to be ensured. The vehicle cannot be expendable even when operating under difficult conditions. [1]

Nature of the industry - ROVs are mostly used in the wealthy oil/gas extraction industry, where companies are able to dish out the large investments required. [1]

2. MARKET ANALYSIS

This section will analyse four existing solutions which have the most significance on the current CROV market or future potential. It should be noted that some assumptions have to be made while analysing the Trident and the iBubble, as these are still in development and so there is limited technical data available. The developing CROV market will be discussed in general as well, to find out how it will progress in the future.

Table 2.1. Main parameters of the ROVs under analysis.

Name	Depth rating, m	Top speed, m/s	Mass, kg	Dimensions, mm	Run time, h	Price, €
OpenROV Trident	100	2	2,9	400x200x80	3	1000
iBubble	60	1	5	500x350x250	1	1800
Hydroview Sport	45	1	4,3	370x480x180	2	5200
Seabotix LV	150	1,5	31	530x245x254	indefinite	~30000

2.1 Comparison

2.1.1 OpenROV Trident

The Trident is currently by far the most developed consumer ROV platform. It is being developed by OpenROV, a company which originates from an online community of ROV hobbyists. Since 2012, OpenROV has been selling of low-cost, do-it-yourself kits ROVs for hobbyists. Using the experience gathered from developing these kits and contributions from the community, OpenROV announced in September 2015 that they are developing a consumer ROV. Crowdfunding was used to finance the project, with their goal being reached within a single day. This fact indicates that there is plenty of public interest towards their project and thus into consumer ROVs in general as well. [2] [3]

Figure 2.1. OpenROV Trident operating underwater. [3]

The Trident is currently still in development at the moment. OpenROV expects to start shipping late 2016. However, video footage of the Trident operating successfully underwater has already been released (still image of the footage shown on Figure 2.1), which serves as an initial proof-of-concept. [3]

OpenROV claims that the Trident is able to move at 2 m/s, which is by far the fastest of the ROVs discussed. These speeds are made possible by its hydrodynamic shape, which minimizes drag forces applied on the vehicle. It is also stated that this kind of shape gives the vehicle more stability while traveling in straight lines. OpenROV considers this capability to drive around in a larger area more important to the recreational underwater explorer who might not be looking for a particular object but wants to explore while driving along. [3]

Figure 2.2. OpenROV 2.8. [2]

The propulsion system of the Trident is also remarkable as it uses only three thrusters. This allows for a higher run time as only three electric motors are used. These are brushless DC motors which are exposed to water. The manufacturer claims that these motors are corrosion-resistant and rated to work even in sea water. [3]

The Trident is controlled via laptop or mobile device. At the moment OpenROV has not specified the particular hardware that is being used on the Trident. However, by taking a look at what could be called Trident's predecessor, the hobbyist-oriented OpenROV 2.8 (Figure 2.2), several assumptions could be made on the Trident's hardware. [2] [3]

For example, the 2.8 is driven by a Linux-running single-board computer, BeagleBone Black. It has a high-definition USB webcam. By looking at sample footage of the 2.8 being operated, it can be seen that the video feed has a disturbingly low frame rate. Also there is noticeable video latency, which means that controlling the ROV does not feel responsive. Unlike the Trident, the 2.8 is not designed for traveling at high speed and therefore these shortcomings may not be a problem to the operator. Problems with the video feed are caused most likely by the USB webcam used (reasons discussed in section 6.1). [2]

Announced run time of the Trident is three hours which is larger than its battery powered competitors. $LiFePO_4$ type batteries are used, which are embedded in the hull. Therefore, the battery unit cannot be simply replaced and so the run time is restrained. Three hours of run time would probably be enough for most use. However it could be a beneficial feature which could make it more appealing to the consumer who, for example, is travelling abroad. When intending to visit different diving sites in a single day, even the three-hour run time may prove insufficient. [3]

2.1.2 iBubble

iBubble is what could be considered the first consumer AUV. iBubble is mainly intended for divers who want to record their dives hands-off from the camera. It has depth rating of 60 m and has a similar form factor as the Trident. As an AUV it does not need a tether, however it also has ROV capability when an optional tether is attached. iBubble communicates underwater with a proprietary wristwatch using low frequencies in order to determine its location relative to the diver. [4]

iBubble has a maximum travel speed of 1 m/s which makes the Trident twice as fast. iBubble has 8 thrusters in total. These are required in order to maximize manoeuvrability as the vehicle constantly has to keep the diver in the view of its camera. Further compared to the Trident, the iBubble is almost twice as expensive as well. This could be explained by the added cost of the wristwatch that has to be used for the AUV functionality of the iBubble. It has only a third of the run-time of the Trident, most likely because the iBubble has 5 more thrusters compared to the Trident, thus causing an increased current draw. [4]

Figure 2.3. iBubble AUV. [4]

iBubble also benefitted from a very successful crowdfunding campaign as their project was funded in a matter of hours, They have also recently shown a working prototype and expect to start shipping the first models mid-2017. Footage of early conceptual testing shows a Raspberry Pi microcomputer being used, which is similar to the BeagleBone Black used on the OpenROV 2.8 and most likely the Trident as well. iBubble has flexible light holders, that provide better lighting adjustability, as opposed to the Trident that has fixed lights right beside the camera. [4]

2.1.3 Hydroview Sport

Hydroview Sport comes from the manufacturer Aquabotix, which is a well-established manufacturer as opposed to start-ups such as the OpenROV and iBubble. Aquabotix mainly produces professional shallow-water OCROVs. The Sport is their most affordable, entry-level solution. [5]

Figure 2.4. Hydroview Sport. [5]

Available already since 2012, the Sport could be considered one of the first commercial recreational ROV, as it is controlled via the user's mobile device. It has a hydrodynamic-shaped hull and 3 thruster configuration, allowing for a 2 hour run time. However, the motors are brushed DC motors, which therefore need to be enclosed from water and are less efficient when compared to brushless DC motors. The thruster configuration is similar to the Trident, allowing for forward, yaw and pitch. It is rated for only 45 m depth which is the least of the lot under analysis. This could be explained by the weak link in the system where the brushed motors extend out of the dry housing – the dynamic seal. [5]

The biggest weakness of the Hydroview Sport is by far its price – at over 5000 € it will not be able to compete with the Trident and the iBubble once they are launched. The high cost of the Sport can be explained by the fact that Aquabotix has been more focused on producing professional OCROVs so that their production is not optimized for creating lower-end products like the Sport. [5]

So far, the CROV market has been very small, allowing the few manufacturers to dictate the higher price. That being said, the Sport has a lot of the features already present that the newer manufacturers are currently developing, for example control via the user's mobile device. Therefore, it is possible that as the market of consumer ROVs expands in the coming years, Aquabotix might use their experience and know-how to develop a more affordable ROV on the basis of the Sport.

2.1.4 Seabotix LBV150-4

Although the Seabotix LBV150-4 is developed primarily for professional use, it is still significant in the CROV market as it is the closest solution to a CROV among professional OCROVs. Due to its popularity, the LBV150-4 is considered the market leader amongst professional OCROVS. Among the other ROVs in the Seabotix product range, the LBV150-4 is the most basic model. Its price point is considerably lower price point compared to the average cost of professional OCROVs. [6]

Figure 2.5. Seabotix LBV150-4. [6]

The LBV150-4 is rated up to 150 m depth, making it the most pressure resistant ROV of the lot. Most likely, high tolerance machined parts are used, which allows for these depths but increases the cost as well. The LBV150-4 has a four thruster configuration. Compared to the three thruster configuration of the Trident and Sport, the extra thruster on the LBV150-4 allows it to do lateral movement, which the Trident and the Sport cannot. LBV150-4 is powered via tether, so its run-time is not constrained at all. However, due to this fact it is dependent on mains power, which greatly restricts the locations it can be used at. [6]

As opposed to other ROVs in this analysis, the LBV150-4 is the only one that requires a proprietary control console. With the mass of the ROV combined with the mass of the control unit, it adds up to 31 kg for the whole system. Therefore it has poor portability compared to the other three. The biggest drawback of this system is however its extremely high price compared to the other ROVs discussed. However, the LBV150-4 has capabilities to attach simple tooling, such as a manipulator arm. Aside the increased depth rating, the latter might be the only valid reason why a recreational user would opt for this ROV when cheaper options are available. [6]

2.2 Market developments

Several conclusions can be made why and how the CROV market will progress in the future. This is important in order to assess the relevance of the topic and to see if developing solutions in this field will be of use in the future.

In general, the market already shows clear signs of growth, as there are several start-up companies developing solutions in this field. For example, OpenROV and iBubble have started their operations only within the past couple of years. There is clear public interest towards consumer ROVs. Measurable proof of this can be seen in the vast success of the crowdfunding campaigns of OpenROV and iBubble as both of them fulfilled their monetary campaign goals in a matter of hours. [3] [4]

Advancements in technology can be considered responsible as well why the CROV solutions are starting to emerge as of now. For example, the availability of low-cost single board computers such as the Raspberry Pi, that deliver high processing power in a small form factor. This combination is necessary for transmitting high-definition video. Also, the development of mobile devices such as tablet computers, which can be used as control equipment, help in the success of the CROVs.

Another reason for further growth of the CROV market is the example of the consumer UAV market, which started out the same way only some years ago. Consumer UAVs started emerging as the technology for their control systems and high energy density batteries became affordable. Alike ROVs are right now, UAVs became highly popular among hobbyists right before the so called “drone revolution”. The existence of the consumer UAV market might be beneficial for the manufacturers of CROVs, as CROVs could be introduced to the consumer as “underwater drones”. It is possible as well, that some of the currently established manufacturers of consumer UAVs will branch out in the future and start developing CROVs.

3. DESIGN CRITERIA

In this chapter, necessary criteria are identified for designing a CROV that would be competitive on the market, based on the benefits and drawbacks of existing solutions found in the previous chapter. The resulting criteria can be used as a reference later in the work, when developing the design concept of the ROV.

3.1 Depth rating

Every extra metre that the ROV is able to go in depth makes it more competitive on the market. However, the cost of materials and manufacturing methods used in mass production, do not allow more than a 100 m of depth, as shown by the example of OpenROV Trident, which has the largest depth rating among the ROVs analysed in the last chapter

In the design phase of any ROV it should be considered that as the depth rating of the vehicle is increased, its costs increase exponentially and therefore it is important to develop the ROV so that it is able to reach sufficient depth without failure while keeping costs as low as possible. Taking these facts into account, the depth rating of the CROV will be established at 100 m.

3.2 Cost

Market analysis has shown that currently the price point of existing CROVs has been established in between 1000 € and 2000 €. Hence, the cost of a new CROV solution also should not exceed this range, in order for the solution to be considered competitive. The cost of most consumer-grade aerial photography UAVs is also located in this range which means that this price range for a consumer-oriented unmanned vehicle has been already accepted. Therefore it will be easier for CROVs to enter the market.

Costs will be kept as low as possible, mainly by using mass producible solutions. No high-tolerance, precision-machined parts will be allowed. Compared to existing OCROVs costs can be also reduced at the expense of control equipment. The CROV will be controlled via the user’s smart device, so there is no extra costs for control equipment.

3.3 Physical properties

Portability is an essential feature for the recreational user and so the entire ROV system must be small enough to fit in the user’s backpack. The system has to be light as well for the user to be able to carry the ROV while hiking for example. Every part of the ROV that has to be in contact with water will have to be corrosion-resistant or easily replaceable.

3.4 Mobility

As opposed to conventional ROVs that are designed with maximum vehicle stability in mind, the CROV should offer the user maximum mobility. As it was mentioned in the market analysis, the CROV should be optimized to travel quickly in a straight line as opposed to most ROVs that are intended for working in a small, pre-determined area.

Therefore, the CROV should manoeuvre rather like an airplane. Therefore, the propulsion system of the ROV should be designed to maximize longitudinal movement. Lateral movement capability is essential with industrial ROVs for retaining correct attitude with regard to a certain work object. However, it can be neglected if need be, as left-right movement is not a priority for the recreational user.

Considering that the speed of sea currents is 1 m/s on average, the top speed of the ROV should exceed that value. In order to have good mobility even in faster currents and to increase competitiveness on the market, the CROV should be able to reach 2 m/s. The Trident is existing proof that this speed can be achieved by a CROV. [7]

3.5 Run time

Considering the specifications of existing solutions, the minimum continuous run-time of the ROV should be set at 2 hours, when opting for on-board power. However, according to currently available data, none of the ROVs discussed in market analysis have capability for easily replacing their batteries on-the-go. Thus, if the CROV would be developed with replaceable batteries, the set run time could be considerably lower.

3.6 Video feed

The video feed from the ROV should be of high-definition quality with negligible lag. It should also display basic telemetry data.

3.7 Maintenance

Any maintenance that the ROV would require has to be made convenient and inexpensive for the user. Least amount of tools, if any, should be required for maintaining the vehicle.

4. MECHANICAL DESIGN

Although various underwater vehicles exist, it can be said that the fundamental principles apply to all submersible vehicles. This chapter describes and analyses the different mechanical aspects of submersible vehicle design from a consumer ROV standpoint.

4.1 Pressure

Hydrostatic pressure exerted on the hull of the vehicle is expressed with the following equation. [8]

$$P = P_a + \rho g h \tag{1}$$

P – hydrostatic pressure, N/m^2,

P_a – atmospheric pressure at the surface, N/m^2,

ρ – density of the water, kg/m^3,

g – gravitational acceleration, m/s^2,

h – depth, m.

The previous equation is likely the most important relation when designing a submersible, as it determines how much pressure the hull of the vehicle has to endure at a given depth.

Taking into account the set design criterion of 100 m maximum operational depth, the hydrostatic pressure that is exerted on the hull of the CROV, can be calculated. Considering the density of seawater and normal atmospheric pressure at surface, the hydrostatic pressure at 100 m of depth calculates roughly to 1,1 MPa. Structural elements of the hull will have to be selected accordingly to withstand this pressure.

4.2 Buoyancy

According to Archimedes' principle, any body partially or totally immersed in a fluid is buoyed up by a force equal to the weight of the displaced fluid. An object that is submerged will either sink or float depending on the summed effect of the weight of the object and buoyant force. This explains why objects, that are less dense than water, float and objects, that are denser than water, sink. When the weight of the submerged object is equal to the weight of the water that it displaces, the object will neither float nor sink. In this case, the object is in a neutrally buoyant state. These three different states are shown on Figure 4.1. With the specific gravity of ambient water considered to be equal to one, the submerged vehicle will float if its specific gravity relative to water is less than one, and sink if its specific gravity is greater than one. [1] [8]

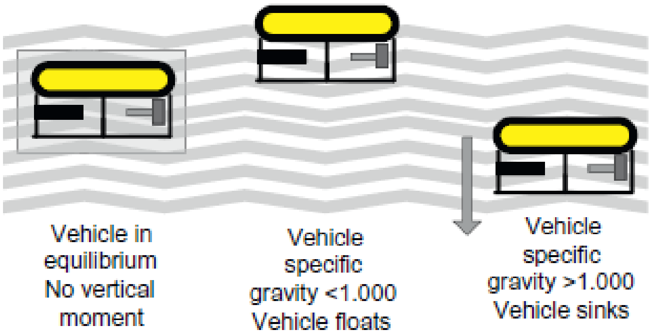

Figure 4.1. Specific gravity versus vehicle buoyancy. [1]

Neutral buoyancy is the ideal state for most submersible vehicles because no work has to be done by the vehicle to maintain given depth. The specific gravity of the vehicle will be close to one, if considering the previous example. Therefore, underwater vehicles are usually adjusted to be neutrally buoyant by either adding weight or buoyancy to the structure, depending on the payload. However, there are systems for varying the buoyancy of the vehicles, which will be further discussed in chapter 5. [1]

The resultant of the forces of gravity acting on parts of the vehicle is centred at a point called the centre of gravity (CG). Similarly, the resultant of the buoyant forces countering the gravitational forces of the vehicle, acting through the CG of the fluid displaced by the vehicle is called the centre of buoyancy (CB). If the CG and the CB of the vehicle are not located on the same vertical axis, the vehicle will not be in equilibrium. Gravitational and buoyant forces acting through CG and CB create a righting moment, causing the vehicle to rotate towards alignment (Figure 4.2). This provides inherent stability to the vehicle. [1]

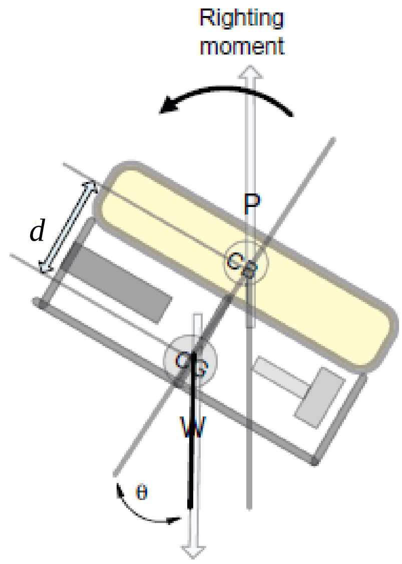

Figure 4.2. Righting moment. [1]

The magnitude of the righting moment is expressed with the following equation. [1]

$$M_0 = W \cdot d \cdot \sin\theta \tag{2}$$

M_0 – righting moment, Nm,

W – weight of the vehicle, kg,

d – distance between CG and CB, m,

θ – angle of inclination of the vehicle with respect to the vertical axis, rad.

The most important fact that equation 2 tells is that the magnitude that vehicle is trying to right its alignment underwater is proportional to the distance between the CG and the CB. Therefore, a certain underwater vehicle can be designed to be less or more inherently stable by varying the distance between the CG and the CB.

Conclusions for designing the CROV can be made from the previous. Firstly, the CROV should be designed so that weight is equal to the weight of the water it displaces when submerged, so it is neutrally buoyant. Secondly, the location of the CG and the CB of the CROV determines how much the vehicle right itself in the water. As the CROV should manoeuvre in the water similarly to an airplane, the discussed inherent vertical stability will be unwanted. Therefore, in order to ensure required manoeuvrability of the CROV, the distance between its CG and CB should be as small as possible to minimize the righting moment.

4.3 Hydrodynamics

$$F_{drag} = \frac{1}{2} \cdot \rho v^2 C_d S \tag{3}$$

ρ – density of the water, kg/m^3,

v – velocity of the vehicle, m/s,

C_d – drag coefficient, unitless,

S - surface area of the body normal to the moving direction, m^2.

Equation 3 is a fundamental relation of fluid dynamics, giving several important insights for efficient design of a submersible [8]. First and foremost, it tells that the drag force exerted on a body moving through a fluid is quadratically proportional to the velocity of the body.

Drag force is also affected by the density of the fluid, and more importantly, by the geometry of the body. Surface area of the body, normal to the moving direction, also proportionally affects drag force applied. Thus, it can be concluded, that drag can be reduced by simply designing the surface area of the vehicle normal to the travel direction to be as small as possible.

C_d is a coefficient that expresses how the shape of the body that is moving in the fluid, affects the drag force. The drag coefficients for different shapes are shown on Figure 4.3. The red arrow shows the direction of the flow relative to the cross-section of the shape. It can be seen that the drag coefficient can substantially vary for different shapes. As a vivid example, if comparing the nearly ideal tear-drop shape and cube, it can be seen that the drag coefficient of the tear drop shape is only 3,8 % of that of the cube. If all other parameters of equation 3 are the same, also the drag force applied on the tear-drop shape will be 3,8 % of that of the cube.

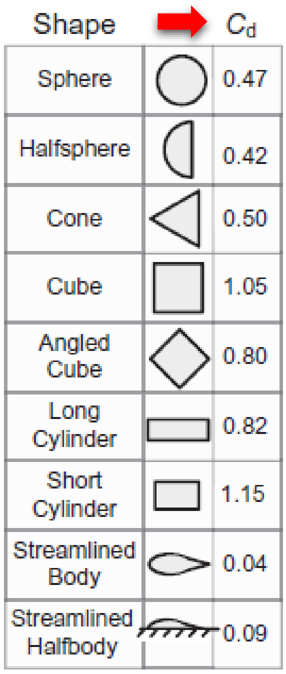

Figure 4.3. Drag coefficients of different shapes. [1]

Therefore, it can be concluded, that hydrodynamic design of the submersible can give tangible and measurable results in terms of reduced drag force. The less drag the vehicle experiences, the less propulsive power is needed, ultimately resulting in improved efficiency, higher speed, more sea-current resistance and longer run-times. [8]

However, the manufacturability of the CROV must be also taken into account as the streamline-shaped structural parts might prove difficult to produce. The shape of the vehicle has to serve as a trade-off between causing the least drag while being well producible.

4.4 Structure

4.4.1 Dry compartment

The purpose of the dry compartment, is to protect parts of the ROV that cannot be exposed to water, for example, the electronics of the vehicle. The dry compartment is made up by a pressure resistant, water-tight canister. [9]

Ideally, there only should be a single dry compartment on the ROV, where all electronics are located. Multiple pressure canisters on a single ROV increase the complexity of maintenance and adds additional possible failure points. However, as it is later described in section 6.6, the CROV needs to have a separate pressure canister for a replaceable battery housing.

Geometry

The sphere is the ideal shape for a submersible, as pressure is distributed evenly on every part of the body and thus, the ideal sphere has no stress concentrators. Difficult and costly to manufacture, spherical pressure compartments are only used on deep-sea submersibles that are made to reach extreme depths. Geometric shapes with polygonal cross-sections and sharp corners, such as a cuboid, should be avoided as this kind of geometry causes an uneven pressure distribution and consequently, stress-risers. [8]

The cylinder is the optimal solution for a pressure canister, combining a good pressure distribution, availability and affordability. Cylinders are the most used shape for pressure compartments among all submersible vehicles, mainly because they can be made from standard parts, such as cylindrical tubing. Many hobbyists use off-the-shelf parts such as PVC piping for their cylindrical dry compartments. For the previously described reasons, cylindrical pressure containers will be most suitable for the CROV. [8]

Sealing

The ends of the cylinders can be sealed using several techniques. Commonly used methods are described in the following. [9]

Firstly, the piston type seal is made by an endcap, which fits tightly in the cylinder (Figure 4.4). An O-ring is seated in a groove of the endcap, providing a watertight seal. A benefit of the piston type seal is the fact that water pressure acting on the exterior of the cylinder slightly compresses its diameter, which presses on the O-ring even more. However, the endcaps have to be precision-machined to high tolerances and have to be smooth and free of any sharp edges in order for the seal to be reliable. Maintaining this type of seal requires care because any defects in the O-ring or dirt caught on it will cause the seal to fail. Therefore this type of seal cannot be considered on the CROV as the vehicle has to be easily maintained. Also, precision machining any part of the CROV is out of the question, in order to keep costs down. [9]

Flange type seal (Figure 4.4) is the most simple of the three types. Depending on the material of the cylinder, a flat flange will attached to the end of the cylinder by means of welding or adhesives. A flat endcap is bolted onto the flange with an O-ring in between the two for a waterproof seal. This seal is simple to manufacture, also easy to maintain and remove, hence it is widely used on different ROVs. For the same reasons, it would be a good choice for sealing the pressure canisters of the CROV. [9]

Thirdly, the jam-jar seal (Figure 4.5) refers to the similar principle used for sealing glass jars by means of a gasket and a lid, that screws down onto the mouth of the jar. With this variation, a threaded endcap is screwed onto corresponding threads on the cylinder. Once again, an O-ring gasket in between the two parts ensures water-tightness. The benefit of this seal is the ease of maintenance as the canister can be screwed open and closed by hand. In order for this seal to have operating depth beyond only shallow water, it as well requires precision machining, rendering this type of seal unsuitable for use on the CROV. [9]

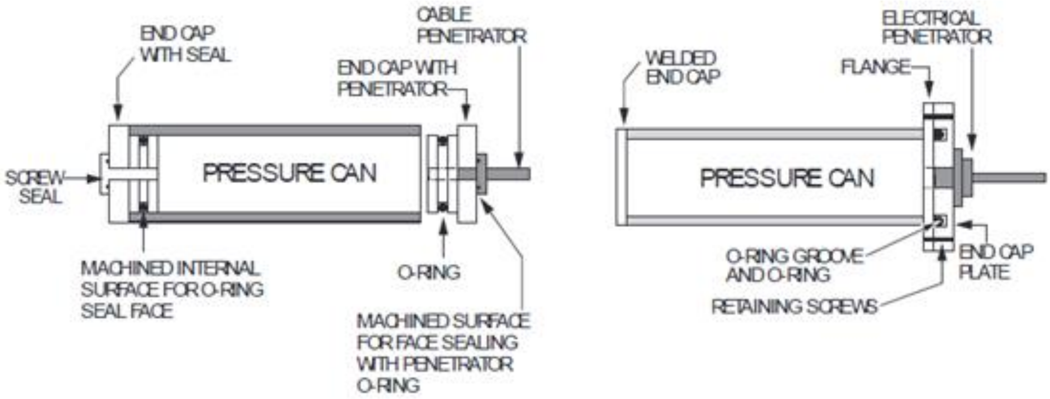

Figure 4.4. Piston type (left) and flange type (right) pressure canister seals. [9]

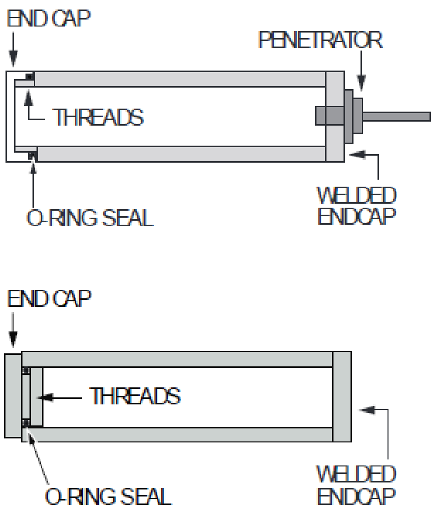

Figure 4.5. Two variations of jam-jar type pressure canister seals. [9]

The collapse pressure of a cylinder is proportional to the wall thickness and inversely proportional to the diameter and length of the cylinder. However, the variation of the diameter influences the variation of the collapse pressure more than that of the length. [10]

Based on this knowledge, conclusions on the proportions of the cylindrical dry compartments can be made, in order to maximize their collapse pressure. Firstly, the diameter and the wall thickness of the cylinder should be kept to a minimum that is required to withstand the maximum operational pressure of the ROV. Therefore, if more space is needed for the electronics, the dry compartment should be extended in the longitudinal axis in order to lose the least of its crush depth. [10]

Cable penetrators

There are a number of cables that have to pass through from the dry compartment out to the water, including the tether, motor and sensor cables, and power cable. The point where the cable passes through the canister introduces a weak link to the canister body, which might cause leakage.

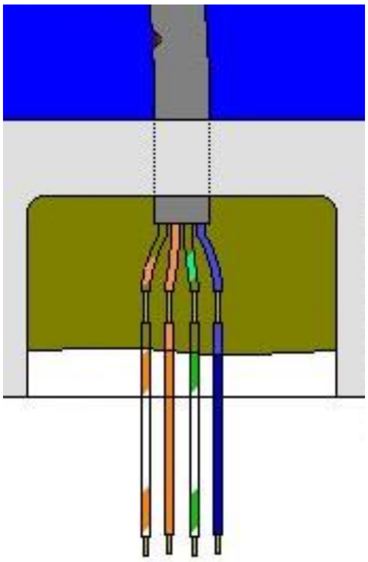

Figure 4.6. Cable penetrator solution. [11]

Considering, that a cylindrical pressure canister is used, it should be noted that the cable penetrators should only be designed on the endcaps of the cylinders. That is because that creating a cable penetrator on a flat face on the endcap will be substantially easier to implement and more watertight than one on the cylindrical face of the canister.

Figure 4.6 exhibits a basic, yet clever solution to pass cables through the hull securely. The point, where the cable passes from the wet environment to the dry is secured by potting the point with epoxy. Note that a length of the insulation of the wires in the epoxy is stripped away intentionally. This is done to prevent leakage through the insulation of the wires in case of the insulation getting damaged. [11]

Humidity

Water vapour will start to condensate on the walls of the pressure vessel as the water temperature drops with increased depth. This phenomenon is unwanted as condensation will block the view of the camera. Placing a pack of moisture absorber, such as silica gel in the dry compartment is an easy and inexpensive way to counter this.

4.4.2 Frame

The frame represents a central hub, onto which other parts are attached. Although, the CROV could be designed to have means for fastening integrated to other parts of the vehicle, so that a dedicated frame is not necessary. This way, unnecessary added mass can be avoided. For example, the pressure canister, being the central part of a small ROV, could have means for mounting the propulsion system.

4.4.3 Fairing

Purpose of the fairing is to change the outer shape of the vehicle in order to lessen hydrodynamic drag. As explained in section 4.3, in order to increase speed and efficiency of the CROV, drag has to be reduced. Therefore, fairing has to be implemented, where doing so would be reasonable, taking into account other design criteria as well besides hydrodynamics. If used, the fairing and the frame of the CROV could be integrated as well, by means of an external, non-pressurized hull of the vehicle. This hull would form a “wet hull” over parts of the ROV, while also providing the vehicle a support structure. Fairing is not used on conventional ROVs due to slow speeds and small travel distances involved. [1]

4.5 Materials

Materials commonly used for underwater vehicles are analysed in the following, in order to determine suitable materials for the CROV according to the structural solutions chosen previously. [1]

4.5.1 Structural

In general, the materials used are chosen to give the CROV maximum strength with the minimum weight, because any weight of the vehicle has to be compensated with buoyancy. As with all other components, the affordability of the materials have to be taken into account.

Ideally, the structural members are made of materials that do not absorb water nor crush under rated pressure of the CROV. They should be impact resistant in order not to break when the CROV should bump into an object. Density of the structural parts of the ROV should be higher than the density of water to act as inherent floatation, in addition to the structural purpose. Corrosion resistance is an important attribute as well for the durability of the vehicle. [1] [8]

Table 4.1. Structural material properties. [8]

Material	Density, kg/m^3	Yield strength, MPa	Tensile modulus, GPa	Specific strength, kNm/kg
Steel (HY80)	7860	550	207	70
Aluminium alloy (7075-6)	2900	503	70	173
Titanium alloy (6-4 STOA)	4500	830	120	184
GFRP	2100	1200	65	571
CFRP	1700	1200	210	706
PMMA	1200	103	3,1	86
PVC	1,4	48	35	34

Metals

Steel has been the most used choice for most submersible vehicles in the past. Its advantages are that the material itself and processing it is cheap relative to other metal alloys. However, it has low specific strength and poor corrosion resistance. The latter is increased with stainless steel alloys but unfortunately so is the price. [8]

Aluminium and titanium alloys, which have been used as well in submersibles in general, have higher specific strength in comparison to steel. Aluminium, however, is prone to corrosion as well. While titanium has excellent corrosion resistance, it is an expensive material. [8] [9]

Plastics

PMMA, also known as acrylic, is transparent and does not corrode in water. Hence it is the most used material for pressure resistant viewports. Also, it is often used as the material of choice for the pressure canister of small ROVs, due to its good mechanical properties and affordability. Therefore, PMMA would be suitable for the pressure canister of the CROV as well. [8]

Composites

Glass-fibre reinforced plastic (GFRP) is the most common composite material for maritime applications. Carbon-fibre reinforced plastic (CFRP) is similar to GFRP, but has more rigidity and a higher specific strength compared GFRP. Alike plastics, composites do not corrode. Composites could be used on the CROV for structural materials, but only if low-cost standard parts are used, such as CFRP tubes. [8]

4.5.2 Floatation

Ideally, floatation materials should have minimum density in order to give the vehicle the most buoyant force to counteract the weight of the vehicle while keeping the volume of the floatation device at a minimum. Most commonly used floatation materials can be divided into two main groups: low-density foam and syntactic foam. [1]

Syntactic foam

Syntactic foam is considered the workhorse floatation material for deep-water (>600 m depth) submersible applications. Basically, syntactic foam is a microsphere structure encased within a resin. Density, and also the durability of the material is determined by the amount of air trapped within the microspheres. For the CROV applications, however, syntactic foam is not the preferred material as the CROV could do with much less depth rating than syntactic foam offers. [1]

Low-density foam

Two types of low-density foams are mostly used in shallow-water submersibles: polyurethane (PU) and polyvinylchloride (PVC) foams. These foams are usually made in both open and closed cell configurations. Closed cell type is more water resistant compared to its open cell counterpart but consequently also denser. [1]

Polyurethane foams, commonly also used for thermal insulation, are mass-produced via continuous extrusion, which makes it an inexpensive material. It can be easily cut into required shapes and covered with coating epoxy and/or paint for additional abrasion and water resistance. PU foams come in a wide range of densities, depending on the application. The density of PIR-type foam, for example, ranges from 29 kg/m^3 to 96 kg/m^3. PU foams have been tested up to depths of 330 metres sea-water (msw). [1]

Alike PU foams, PVC foams also come in different densities and configurations. They can be processed easily as well. For example, the Divinycell HCP is a PVC foam particularly designed for subsea applications. These purpose-designed foams are obviously more expensive than the insulation-grade PU foam. However, the PVC foams excel in terms of depth rating – for example, the maximum operational depth of the HCP line of foams is rated up to 1000 m. Density of these foams ranges from 200 kg/m^3 to 400 kg/m^3. [12]

Compared to syntactic foam, PU and PVC foams are produced in larger quantities at a time and are thus more commonly available and less expensive. For the maximum depth of the CROV (100 m), even the discussed PVC foam has excess depth rating, therefore the cheapest option of PU foam will be sufficient. [1]

4.6 Conclusion

In this chapter, several critical mechanical design considerations were identified which have to be followed in order for the CROV to be able to comply with the design criteria. Structural solutions that would be suitable for the CROV were found, along with material choices.

5. PROPULSION

This chapter will discuss and analyse commonly used means of propulsion of ROVs to identify a suitable solution for the CROV.

The propulsion system is a critical design consideration for any ROV as without sufficient thrust, the vehicle can become overwhelmed by environmental conditions and thus unable to perform the desired tasks. [1]

It should be reminded that the manoeuvrability and top speed of an ROV is highly dependent on the properties of the vehicle hull. As identified in chapter 4.3, the drag force exerted on a submersible increases quadratically as its speed increases. Therefore, the propulsion system of an ROV has to be able to generate equal or more thrust force in order to keep moving forward. The maximum speed of an ROV is hence limited by the maximum thrust force capability of the thruster solution and the hydrodynamic properties of the vehicle body. Horizontal movement of the majority of ROVs and AUVs is realized by thrusters, while the vertical movement is done by either thrusters or a variable buoyancy system. [8]

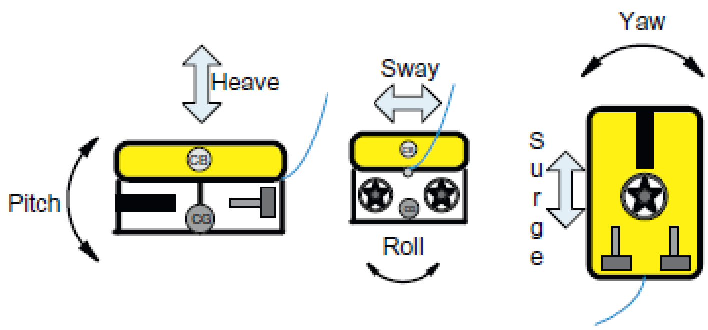

Figure 5.1. Possible motions of an ROV. [1]

Terms used to describe the motions of the ROV are as follows: three translations (surge, heave, and sway along the longitudinal, vertical, and transverse (lateral) axes, respectively) and three rotations (roll, yaw, and pitch about these same respective axes). [1]

Using these terms, according to the design criteria, the aim of the propulsion system of the CROV would be to maximize the surge speed of the vehicle while the sway and heave translational motions can be neglected. From the rotational motions, the CROV should be able to do at least yaw and pitch, while roll is less important.

5.1 Diving

Diving of underwater vehicles is done in two main principles: static or dynamic diving.

Static diving

Static diving methods allow the vehicle to alter its buoyancy in order to ascend or descend (heave). Therefore, the vehicle is able to hover without propulsion. The simplest method of variable buoyancy is the piston ballast tank. It consists of a cylinder and a movable piston. By moving the piston, the volume of the ballast water tank is changed. The vehicle becomes less buoyant as more water is taken into the tank and vice versa. [8]

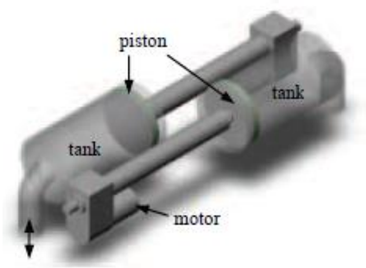

Figure 5.2. Piston ballast tank. [8]

Static diving is less accurate and responsive compared to dynamic diving because the change of buoyancy takes place over a period of time, whereas the effect of the thruster can be noticed almost immediately. As highly responsive control is required for the CROV, static diving should not be implemented. [8]

Dynamic diving

Using thrusters for vertical movement is considered a dynamic diving method. The benefit of using thrusters is a faster and more responsive control of the dive. In this case, in order for the vehicle to hover, it has to be nearly neutrally buoyant. Most ROVs, which use thrusters for depth control are configured to be slightly positively buoyant, as an intrinsic failsafe feature so that the vehicle will ascend to the surface on its own in case of power failure. However, this means that the thrusters need to be constantly working to keep the ROV at depth, consuming power at all times. Dynamic diving provides the quick control response desired for a CROV and thus it is the preferred choice. [8]

5.2 Layout

The amount of thrusters used and their location on the ROV determines the possible movements of the vehicle. Always the minimum number of thrusters should be employed for a set of possible manoeuvres, in order to increase efficiency and save on weight of the CROV. Commonly used thruster configurations are analysed in the following. [1] [9]

5.2.1 Horizontal

Three is the minimum number of fixed thrusters in order to realize both horizontal and vertical movement (Figure 5.3). The two horizontal thrusters are run both in the same direction for surge and in opposite directions for yaw. A single vertical thruster does the heave motion. Usually, the vertical thruster is placed on the same vertical axis with the CG, in order to avoid inadvertent pitch or roll motions while moving vertically. This configuration is unsuitable for industrial ROVs because they require lateral movement to carry out work tasks. However, this simple configuration could be appropriate for the CROV due to its simplicity and the fact that lateral movement is not a priority for the CROV. For example, the OpenROV Trident uses exactly the same three-thruster configuration shown on Figure 5.3. [1]

Lateral movement (sway) could be done if a fourth horizontal thruster is added (Figure 5.3). This configuration is popular among small OCROVs as it offers side movement capabilities by using a single thruster. [1]

On the five thruster variant (Figure 5.3), also called the vectored thrust layout, the horizontal thrusters are placed at an angle and work simultaneously for all manoeuvres. By varying the speed of the individual thrusters, the ROV can move in any direction on the horizontal plane. This layout provides the most precise movements and is therefore used on professional ROVs that operate tools underwater. However, the angled placement of the thrusters decreases efficiency and does not allow for high surge speed. The CROV does not use any tooling, therefore high-precision manoeuvrability is not needed. Maximum longitudinal speed and efficiency are priorities for the CROV, so it can be concluded, that the discussed four- and five-thruster horizontal layouts are not optimal for the CROV. [1]

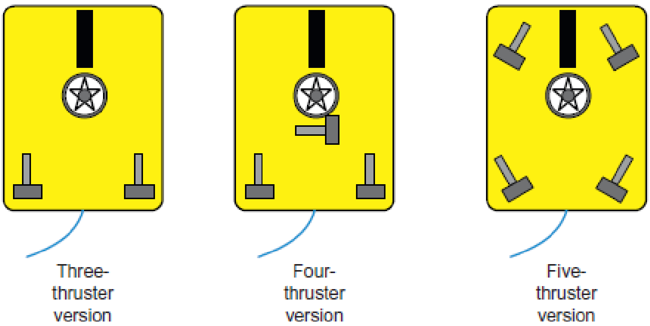

Figure 5.3. Commonly used ROV thruster configurations. [1]

5.2.2 Vertical

Unlike submarines, ROVs are usually not capable of pitch and roll movements as they have to remain stationary in order to perform work. For that reason, they are optimized towards stability instead. As said before, the CROV will have to manoeuvre rather like an airplane rather than a regular ROV and therefore pitch and roll capabilities have to be included. [1]

If pitch and roll movements are to be done, additional vertical thrusters need to be added. In a similar manner as with horizontal thrusters, pitch and roll movements are done via asymmetrical thrusting of the vertical thrusters. [1]

5.2.3 Positioning

The exact locations of the thrusters with regard to the centre of gravity (CG) and the centre of drag (CD) have great effect on the dynamics of the vehicle. Ideally, both the horizontal and vertical thrusters should be located in line with the CG, in their respective planes. Otherwise, a moment will occur, between the thruster and the CG, causing unwanted rotational movement. [1]

For example on Figure 5.4, it can be seen, that the heave motion of the ROV will not cause any unwanted rotation as the centre of gravity and centre of drag are on the same axis with the vertical thruster. However, when attempting surge motion, an unwanted pitching motion of the vehicle is caused, due to the fact that the CG and CD are not in line with horizontal thrust. As both CG and CD are off the said axis in the current example, they both cause a moment, with opposite sign. Direction of the unwanted pitch rotation of the ROV is determined by the sum of these moments.

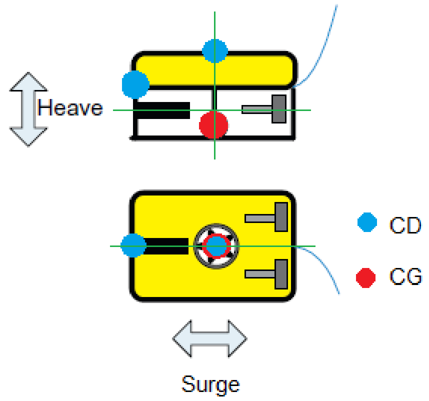

Figure 5.4. Simplified example of thruster positioning with regard to CG and CD. [1]

However, the previously described phenomenon does not always have to be considered an adverse effect caused by misplaced thrusters. When considering again the manoeuvrability requirements of the CROV, it should be noted, that the vehicle could dive via pitching down or up and then surging. Thus, separate heave motion is not required. Considering the same three thruster layout as described before, pitching capability can be simply added by intentionally placing the single vertical thruster out of line with the CG and CD.

5.3 Thruster

Alike other marine vehicles, an ROV thruster mainly comprises of a motor-propeller combination. By far the most common thruster motor on OCROVs is the DC motor, due to its power, availability, variety, reliability and ease of interface. [1]

5.3.1 Motor

Brushed DC

Brushed DC (BDC) motors are the most commonly used electric motors for small applications in every field. They can be easily operated and do not require special control hardware for fixed speeds. Compared to brushless DC motors, they have a lower cost but also a considerably lower efficiency. Periodic maintenance is required due to brushes wearing out. [13]

Brushed DC motors cannot run submerged, as the brushes are basically exposed contacts. In conductive salt-water, a short circuit will be created. The BDC motor has to be sealed in a waterproof housing submerged operation. Also, a dynamic seal has to be created at the point where the motor shaft penetrates through the housing for propeller mounting, allowing for rotation of the shaft. However, this seal poses a weak link in the system.

Inexpensive ROV thruster solutions that use brushed motors include marine bilge pumps. These are inexpensive, often used on hobby ROVs. However, their maximum depth rating is around only 10 m and thus cannot be considered to be used on the CROV.

Brushless DC

Brushless DC (BLDC) motors offer more reliability and efficiency compared to BDC motors due to the absence of brushes. BLDC motors are usually more powerful than a BDC counterpart of the same form factor. Drawback of the BLDC motor is the fact that it needs special control circuitry for operating at all. Often used on radio-controlled models, small BLDC motors are inexpensive and with a number of different configurations available. [13]

The main benefit of BLDC motors in context of the CROV is the fact that they do not have any exposed electrical conductors, hence they can be run submerged in water. Metal parts will corrode in sea-water if the motors are run as-is. Corrosion resistance can be improved by using a sealing compound to cover parts prone to corrosion and replacing stock bearings with ceramic ones.

5.3.2 Propeller

The aim of the propeller is to convert the rotation of the motor to thrust. Propellers come in various shapes and sizes depending on their purpose, whether they are optimized for larger speed or torque. As with electric motors, a large variety of small propellers, that would be suitable for small ROVs are used on radio-controlled boats.

5.3.3 Thruster choice

The choice of thrusters should be one of the final decisions during the design phase. That is because in order to choose appropriate thrusters, the drag force exerted on the vehicle must be known. Hence, the thrusters can only be accurately chosen once the mechanical parts are done.

Considering that the drag force is known, a suitable motor-propeller combination would have to be chosen. As the mentioned cheap motors and propellers are not usually sold in bundles to produce a certain value of thrust, and come with only limited technical data, the thrust produced by a given combination can only be estimated. Therefore, the best method, that guarantees accurate data of a certain motor-propeller combination, is to carry out actual tests to measure the thrust produced.

5.4 Conclusion

In this chapter, suitable means of propulsion were identified for the CROV. Thrusters were found to be suitable for both vertical and horizontal movement. Different thruster layouts were analysed and a suitable one was chosen. The importance of correct positioning of the thrusters was found.

6. ELECTRONICS

This chapter will discuss the electrical parts required for an ROV to function while considering the set design criteria.

6.1 Camera

Market analysis has shown that a high-definition live video feed is mandatory for the CROV to compete with existing solutions. Moreover, the CROV should have a better video feed in terms of latency and frame rate. Possible solutions for the camera of the CROV are discussed in the following.

Table 6.1. Comparison of possible CROV cameras. [14] [15]

Camera	Resolution	Interface	Price, €
Logitech C525	1280x720	USB	24
HS1177	976x494	Analogue	31
Raspberry Pi camera module	1920x1080	CSI-2	35

6.1.1 USB webcam

USB webcams are widely used as inexpensive cameras for transmitting a digital HD video feed, in surveillance systems for example. USB cameras first do internal processing in order to send data to the host computer, where it is further processed before it is finally displayable. This causes latency in the video feed. Also, it places a considerable load on the GPU of the host computer. [14]

6.1.2 Analogue CCTV cameras

CCTV cameras have also been used in surveillance systems for decades. CCTV cameras are able to produce only low-resolution video. They use an analogue interface, therefore no digital processing is done and negligible latency is caused (30 ms on average). For this reason, CCTV cameras are the most commonly used cameras for the live video feed of UAVs, where video latency larger than 100 ms is considered unacceptable. [15]

6.1.3 Raspberry Pi camera

The Raspberry Pi microcomputer has a separate camera module that is capable of HD video. Compared to USB cameras, considerably less latency is introduced to the video stream because the Raspberry Pi camera is connected directly to the GPU of the Raspberry Pi itself, via CSI-2 interface. Therefore no internal processing is done in the camera – the raw image data is streamed right to the GPU of the Raspberry Pi, allowing for a low-latency HD video feed. The drawback of this camera is that due to the uncommon CSI-2 interface, a controller is required that has CSI-2 capability as well. [14]

6.1.4 Conclusion

Examples of the different camera types discussed in the previous subsections are brought in Table 6.1. It can be seen that all of the cameras locate in a similar price range. Resolution-wise, the Raspberry Pi camera is the only one that delivers full-HD video. The HS1177 has the lowest video resolution, while it is the only camera in the comparison that does not impose demands for the controller. Overall, Raspberry Pi has the best features in terms of fulfilling the requirements for having a low-latency, high-resolution video from the CROV.

6.2 Main controller

The main controller acts as a central hub of the electronics of the ROV, controlling thrusters, reading data from sensors and transmitting a video feed to the user. As discussed in the previous subsection, the HD video feed demands the most resources from the controller. A simple microcontroller such as an Arduino could be used for controlling thrusters and sensors, if the ROV was to have an analogue video feed. In the CROV case, the controller must have the CSI-2 camera interface and sufficient processing power. Choice of the camera narrows down potential controller candidates as most single-board computers do not have a CSI-2 interface and therefore the Raspberry Pi itself is the most suitable candidate.

Table 6.2. Raspberry Pi 3 Model B main specifications. [16]

CPU	Quadcore ARM Cortex-A53, 1.2GHz
GPU	Broadcom VideoCore IV
RAM	1GB LPDDR2 (900 MHz)
Networking	10/100 Ethernet, 2.4GHz 802.11n wireless, Bluetooth
Storage	microSD
GPIO	40-pin header
Ports	HDMI, 3.5mm analogue audio-video jack, 4× USB 2.0, Ethernet, Camera Serial Interface (CSI), Display Serial Interface (DSI)
Dimensions	86 mm x 55 mm x 18 mm

Aside from the CSI interface, the Raspberry Pi offers other benefits as well and would be a viable option even if another type of camera was to be used. Main technical specifications of the latest Raspberry Pi model can be seen in Table 6.2. It has a small form factor, so that the dry compartment can be made with smaller dimensions. It supports HD video transmission, has a large number of I/O pins and multiple means for networking.

6.3 Motor controllers

As concluded in chapter 5, the CROV will use brushless DC motors. Therefore, electronic speed controllers (ESC) for these motors have to be provided. Each motor requires a separate ESC. Alike motors and propellers, a large variety of ESCs is available at a low cost from various radio-controlled model vendors. The most important parameter of an ESC is its current rating. For the ESC to be able to run the motor for a prolonged time without overheating, the ESC has to be rated for at least the amount of current the given motor-propeller combination will draw at maximum load.

Communication with the ESCs is usually done via PWM or I^2C. Although the Raspberry Pi has capabilities to produce a PWM signal, the ESCs should be controlled via I^2C because sensors of the CROV will also be communicating on the I^2C bus (further explained in 6.5).

6.4 Lighting

As the ROV goes further in depth, the less light there is. Thus, a lighting system needs to be fitted on the ROV. Ideally, the lighting system would provide enough light for the CROV to operate even in pitch black darkness, while consuming the least amount of power.

Positioning these lights also needs consideration. For example, if the ROV is running near the bottom, the thrusters can swirl up silt particles. If the lights are right beside the camera, they will light up the particles right in front of the camera so that further objects cannot be seen. Therefore, the lights should be located further away from the camera so that the close proximity of the camera will not be illuminated. [1]

6.5 Sensors

Giving telemetry data to the user is not a mandatory functionality of the CROV, as it could be successfully operated using only the information provided by the camera. Although, the functionality of the vehicle can easily be enhanced by providing telemetry data. Therefore, basic sensors will be implemented on the CROV. As the sensors on the CROV are used only to enhance user experience and provide reference data, the performance characteristics of the sensors can be low in order to minimize costs. [8]

For the sake of simplicity, all sensors on the CROV should communicate with the main controller using the same protocol. I^2C is commonly used among all types of sensors. It is also supported by the Raspberry Pi, therefore all sensors should be selected so that they have I^2C capability.

6.5.1 Pressure sensor

The first and most basic sensor of any submersible is a hydrostatic pressure sensor. Sensed pressure can easily be converted into depth by using equation 1. A suitable pressure sensor should be selected taking into account the operational depth range of the CROV. [8]

6.5.2 Leakage sensor

The leakage sensor is meant as a failsafe in order for the user to know about water ingress into the dry compartments right when it occurs. Without it, the ROV could run for a long period of time without the operator noticing the issue until irreversible damage is caused. The sensor allows for quick detection of the problem and surfacing of the ROV before critical failure. [8]

Due to the expendable nature of the CROV, any failsafe means could be neglected if they would involve unwarranted costs. However, this is not the case, as inexpensive humidity sensors are available.

Humidity sensors should be placed both in the main electronics compartment and battery compartment. The main controller will read data from it and raise an alarm once a certain value has been reached.

6.5.3 Magnetometer

The magnetometer provides the means to calculate the heading of the CROV, like an electronic compass. Heading data given to the user as on-screen telemetry will help the operator in navigating underwater.

6.6 Power supply

The power system of the ROV is responsible for supplying power to all electronics of the vehicle. Design of the power system has to start from the consumer-end of the system. The power consumption of individual components has to be identified, in order to be able to provide sufficient power. [8]

6.6.1 On-board *versus* off-board

An on-board power source has to be used on the CROV to ensure portability. If powering the CROV through the tether was to be considered, AC would have to be used, in order to increase the efficiency of the power transmission. This consequently creates the need for mains power. As the user should be able to deploy the CROV in any given location, regardless of access to mains power, it is concluded that a CROV should be powered on-board. [8]

6.6.2 Battery

First and foremost, the battery of the CROV has to be rechargeable. It has to be able to supply the amount of current drawn by the electronics. Therefore, all other electrical parts should be chosen before the battery, so that their summed power consumption can be used to choose a battery. The nominal voltage of the battery has to be equal to or higher than the highest rated voltage of a given power consumer in the system, as the voltage can be regulated down for lower-voltage consumers. [8]

Currently, the best combination of affordability, high energy density and high discharge rate is found in the lithium-polymer (li-po) batteries. The mentioned qualities make these batteries the preferred choice for smaller UAVs. Li-po batteries are available in a wide range of voltage and capacity configurations. The drawback to li-po batteries is their lack of safety. If used improperly, for example, overcharged or over-discharged, they can rapidly catch fire. [17]

Lithium iron phosphate ($LiFePO_4$) represents a safer alternative to li-po batteries. $LiFePO_4$ batteries do not catch fire in the event of overcharging or over-discharging, and can be used for more charge-discharge cycles compared to li-po batteries. Their drawback is that $LiFePO_4$ batteries have slightly lower energy density and discharge characteristics when compared to li-po batteries. [17]

Ideally, the mass of the battery should be as low as possible. However, if weight needs to be added to achieve neutral buoyancy for a certain CROV design, instead of dead weight, a larger battery pack could be implemented, consequently creating additional run-time for the vehicle.

6.7 Tether

Every single ROV system currently in use, irrelevant of its size or purpose, has a wired link between the vehicle and operator. In addition to control and video signals, most professional ROVs are also powered via tether. [1]

6.7.1 Mechanical considerations

Generally, the tether has to comply with the same mechanical requirements as other structural parts of the ROV. For example, ideally, the tether should be neutrally buoyant and as hydrodynamic, so that it would not have an adverse effect on the mobility of the ROV. Materials that are used on the tether also have to be rated for high-pressure submerged operation. For example, the tether cannot lose its buoyancy under pressure. [1]

If the tether would be offset from neutral buoyancy, it would either sink or float, hindering the mobility of the ROV as a consequence, as the offset force of gravity or buoyancy of the tether imposes an additional load on the ROV. Also, a sinking tether can a lot more easily get stuck into objects. [1]

A simple way to improve the buoyancy of the tether would be to attach floats at certain distances along its length. This is inexpensive to realize, however it substantially increases the volume of the tether, making it bulky and not well portable. Another option would be to use neutrally buoyant cable. This cable comprises of wire conductors, which are coated with an elastic floatation material. This purpose-made cable has ideal physical properties for the CROV as the floatation material is integrated into the cable. However, it is a relatively expensive option, for example the current retail price at the OpenROV store is 5 dollars per metre of twisted pair neutrally buoyant cable. [18]

As the ROV goes further in depth, more tether has to be fed into the water. Therefore the surface area of the submerged tether increases as the ROV descends. According to equation 3, the drag force exerted on the tether also increases in relation to the depth of the ROV. Therefore it is critical to reduce the tether diameter. Fortunately, the CROV uses on-board power, thus the tether will only contain data cables which carry negligible amounts of current and the conductors used can have a small cross-section. For this reason, the overall diameter of the tether of the CROV will be small, as thicker power cables do not have to be included. [1]

Aside from the behaviour the tether has while it used underwater, it needs to have suitable parameters outside of the water as well. The dimensions of the packed cable as well as its mass have to be as small as possible to ensure portability.

6.7.2 Communication

Alike many other electrical parts of the CROV, the main requirements for the tether are imposed by the HD video feed. Thus, the suitable communication protocol would have to be able to support the data transfer rates required. Also, the maximum distance that a certain protocol can support has to be taken into consideration, as the maximum allowed tether length was established at 100 m.

Taking these aspects into account, Ethernet is the first protocol that suits the said requirements. Although it is the maximum intended cable length for Ethernet, using it over 100 m is possible. Benefits of using Ethernet includes compatibility with various devices such as routers, PCs or even the Raspberry Pi which has an onboard Ethernet port. This means that if the Ethernet cable (CAT5) was to be used as tether, it could plug directly in to the Raspberry Pi, allowing for a clean and simple setup.

The downside to this are the physical properties of the CAT5 cable itself. It uses four conductors at a minimum as well as a plastic sleeve, all of which result in the cable being negatively buoyant. Adding floats to the cable is not considerable, as its diameter is 5 mm thick already. Floats added would act as a hydrodynamic resistance, which is unwanted. Neutrally buoyant CAT5 cable is not readily available. Although it likely could be manufactured as a custom order, which would prove costly and hence unsuitable for the CROV. [1]

Fortunately, there is an alternative. Powerline communication (PLC) equipment could be used to employ a single twisted pair of wires for Ethernet communication [19]. This can be realized using two powerline Ethernet adapters on both sides of the tether. PLC adapters are commonly used for sharing a local area network over the mains powerline of a building. For the CROV, they could be modified to carry data over a pair of wires. Using this technology effectively reduces the number of conductors in a tether to only two.

6.8 Topside

The purpose of the topside devices is to connect the user's mobile device wirelessly to the tether. Thanks to the compatibility of Ethernet with different communication devices, it is possible to connect the surface-end of the tether with a router for creating a wireless access point. Small, battery-powered routers are available for low-cost. [20]

6.9 Conclusion

In this chapter, an analysis of all the necessary electrical parts of the CROV was carried out. Key problems and considerations concerning each of the components were identified and solutions were given accordingly. The electrical components previously discussed are combined on a conceptual schematic, shown in Appendix 1.

7. PROTOTYPE DESIGN

On the basis of the CROV concept presented previously, a preliminary mechanical design has been developed. It comprises a 3D CAD model along with basic simulations to assess the feasibility of the design. However, it should be noted that the prototype has not yet been fully developed, as it was not the main objective of this thesis.

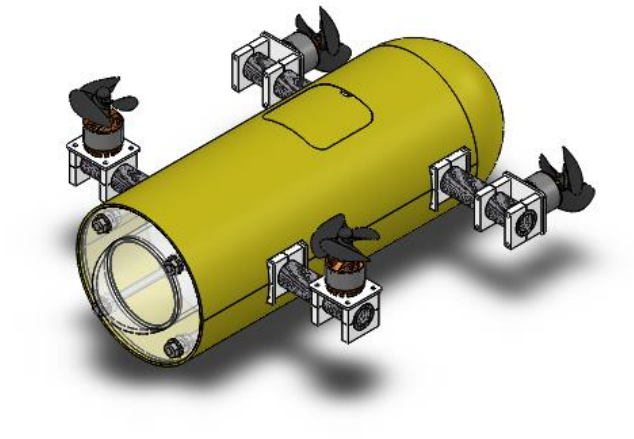

Figure 7.1. CROV prototype CAD model.

7.1 Chosen solutions

This section will describe the solutions chosen for the prototype. All design choices have been made according to the design concept described previously. Therefore, most of the reasoning for the proposed solutions will not be given in this chapter, as it has already been discussed in the previous chapters.

7.1.1 Structure

All mechanical sub-assemblies of the ROV attach onto a common set of threaded rods that pass throughout the vehicle. These rods are also used for sealing the electronics compartment so that separate bolts are not needed. This allows for a clean and highly modular setup. Different modules could be added or interchanged, for example, additional pressure canisters or thrusters could be added on the same “rails”, simply by increasing the length of the rods. Therefore, this structural arrangement is not limited only for the CROV, but could be used on larger ROVs (and AUVs) as well.

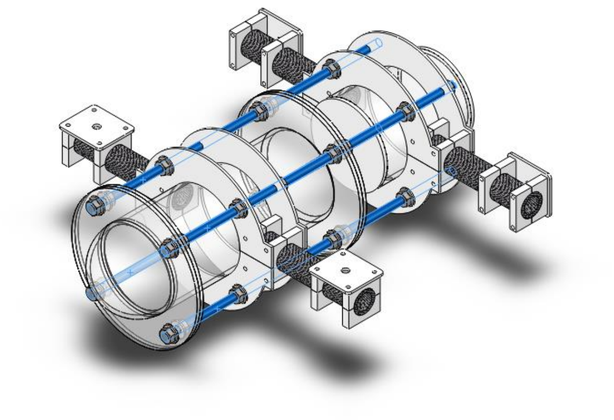

Figure 7.2. Structure of the CROV with the threaded rods highlighted in blue.

As the modules are fastened on the threaded rods using nuts, their position along the longitudinal axis of the CROV can be adjusted. Thus, the positions of the CG and the CB are also changed. This is most important in the initial testing of the CROV, allowing for tuning of the vehicle, in order to achieve best static (neutral buoyancy) and dynamic (manoeuvrability) characteristics. Additionally to the existing modules which inherently affect the CG and the CB of the vehicle, special floatation modules made of buoyant material could be added on the rails as well, if weight compensation would be needed.

7.1.2 Dry compartments

Cylindrical pressure canisters are used both for the main electronics compartment and the battery compartment (Figure 7.3). Flange-type sealing is used for the electronics compartment to ensure maintainability. The flanges are fixed onto the cylinders using marine epoxy. In this initial design the battery compartment, however, will be considered to be sealed shut with epoxy. This is can be done as the batteries do not need to be taken out of the compartment for neither charging nor maintenance.

Lids are bolted onto both ends of the electronics compartment with the structural threaded rods and nuts. The front lid is a hemispherical dome (for reducing drag), while the back lid is a flat plate. The diameters of the adjacent lids and flanges are dimensioned so that there is room for both the mounting holes and an O-ring for sealing.

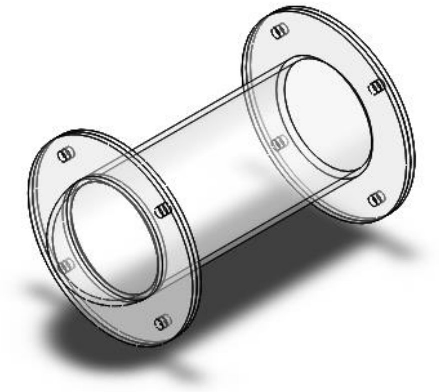

Figure 7.3. Main electronics compartment with lids

The diameter of the electronics compartment is taken according to the width of the Raspberry Pi, as it occupies the most space. The length of the tube is an estimate, taking into account the dimensions of the Raspberry Pi and the camera, while leaving room for ESCs and additional components. A longer cylinder can easily be implemented if more space is required.

Wall thickness of the compartment is dimensioned using Under Pressure, which is a custom made software for calculating the crush depths of pressure housings. After calculating through different tube configurations, the optimal dimensions for the electronics compartment of the CROV were found to be 70 mm outer diameter, 150 mm length and 3 mm wall thickness. The diameter of the flange is 120 mm. Considering this configuration, the depth, where the compartment fails (due to buckling), was given by Under Pressure to be at 110,96 m. This configuration leaves room for error when considering the 100 m maximum operational depth of the CROV. [21]

As the diameter and length of the battery compartment will be smaller than those of the electronics compartment, it can be concluded without calculating, that with the same wall thickness the battery compartment will have a larger crush depth compared to the electronics compartment.

7.1.3 Thruster mounts

Design of the thruster mounts (Figure 7.4) is inspired by motor arms commonly used on multicopter UAVs. Thrusters are clamped onto cylindrical arms that attach to a central hub. The hub is made up of several pieces so it can be seated on the dry compartment as well, in order to get past the flange of the compartment.

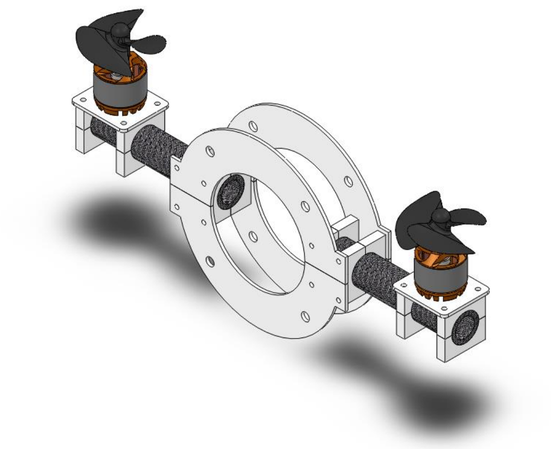

Figure 7.4. Thruster mount assembly.

This arrangement is also easily configurable. For example, the distance between the thrusters could be increased by simply replacing the cylindrical tubes for longer ones as all other hardware remains the same. Also the angle of the thrusters can be changed easily by fastening the motor mounts at a different angle with regard to the central hub of the thruster mount assembly. This allows for using exactly the same hardware for both the horizontal and vertical thruster assemblies.

7.1.4 Fairing

Due to the fact that the modules are placed behind one another, the frontal surface area is kept to a minimum. However there is a number of open cavities between the different modules, which cause drag. Fortunately, thanks again to the uniform arrangement of the modules, a simple cylindrical wet hull can be used to cover the open spaces.

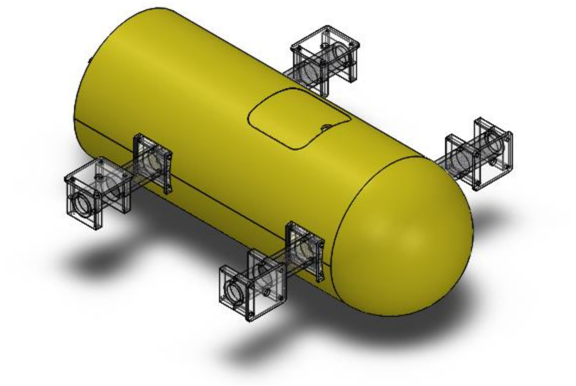

Figure 7.5. Fairing assembly.

Figure 7.5 shows the fairing assembly. It consists of two cylindrical halves and a hemispherical dome. The dome can be removed for replacing the battery, which is located at the rear of the vehicle. The top cylindrical half has a maintenance hatch for connecting the battery cable with the main electronics compartment.

7.2 Simulations

7.2.1 Pressure analysis

Solidworks Simulation software was used to further check the design of the electronics compartment. Buckling analysis was done as buckling was identified as the failure mode during dimensioning calculations. The pressure was defined as 1,1 MPa, which roughly corresponds to 100 m of seawater depth. The following results were obtained from the simulation.

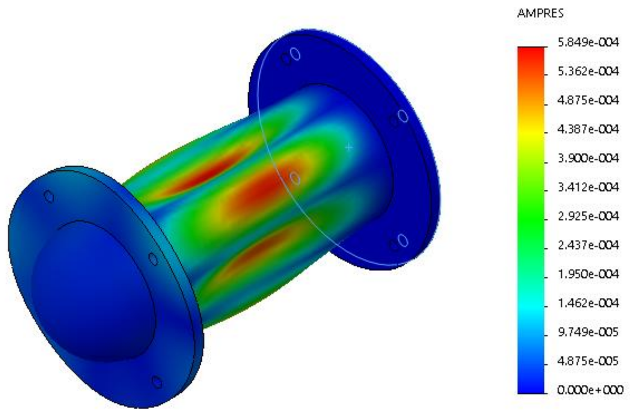

Figure 7.6. Results of buckling analysis

Buckling of the compartment is visualized on Figure 7.6. This analysis yielded a critical load factor of 1,0554. This means that according to the simulation, the compartment will fail under a pressure load that is equal to the applied pressure multiplied with the critical load factor. In this case, this calculates to roughly 105 m depth.

This value is slightly lower than the failure depth calculated by Under Pressure software. However, as the two values are relatively close and both exceed the maximum operational depth of the CROV, the results can be considered valid. Based on these results, it can be concluded that this configuration of the electronics compartment is suitable for being used on the CROV.

7.2.2 CFD

Computational flow dynamics (CFD) analysis has to be carried out for the following reasons. First and foremost, it is required to find the drag forces applied on the hull, in order to determine the thrust force value that the thrusters must generate in order for the vehicle to reach the specified surge speed. Secondly, it can be used to determine how much the added fairing elements affect overall drag force, in order to assess if they give desired results and fulfill their purpose or not.

Solidworks Flow CFD software was used for carrying out these simulations with the developed CAD model. Prior to simulation, several parameters had to be defined. Firstly, the fluid type was set to water. Then the direction vector of the fluid flow was defined normal to the front face of the developed CAD model. Finally, the computational domain of the simulation had to be defined for the software to determine the space where calculations are to be done. In order to decrease computational load and hence calculation times, the computational domain was defined to be only slightly larger than the outer dimensions of the model. Also, the drag force along the corresponding axis was designated as a simulation goal, so that it could be measured after the simulation has finished. After that, the simulation was ready to be started. Using the method previously described, simulations were done in five different configurations. Measured drag force values in the different cases are brought in Table 7.1.

Firstly, it was analyzed how much the drag force varies when either a flat or a hemispherical front endcap is used for the dry compartment. This is important in order to know if the drag force reduction offered by the hemispherical endcap is reasonable to justify its increased cost when compared to the simple flat endcap. Simulation results are shown in Table 7.1. It can be seen that the hemisphere significantly influences the overall drag force. In the case when the hemispherical endcap is used, the drag force value is roughly 32 % lower than that of when the flat endcap is used.

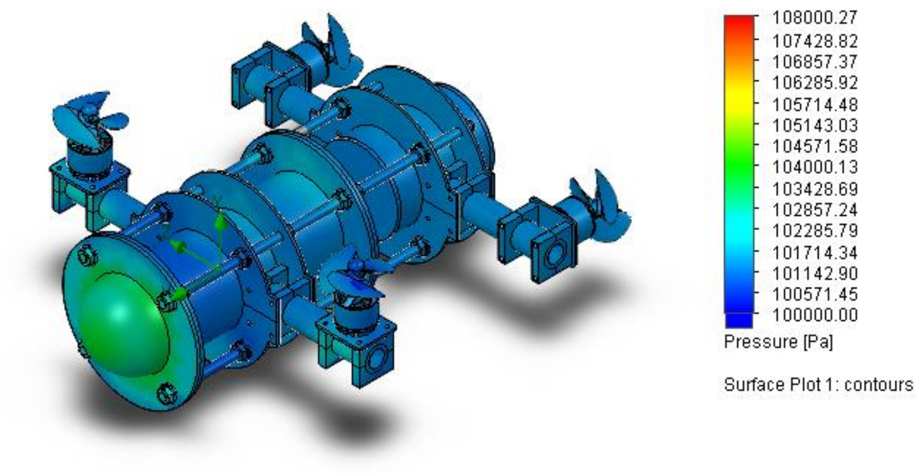

Figure 7.7. Pressure distribution on the ROV during longitudinal movement

The significance of the endcap when speaking of the hydrodynamics of the current design can be further explained by the pressure distribution when the vehicle is moving forward. As seen on Figure 7.7, the most pressure is concentrated on the front endcap and therefore its geometry has great effect on the overall drag.

Table 7.1. CFD analysis results

Speed, m/s	Fairing	Dome	Drag, N
1,5m/s	Yes	Yes	38,48
1,5m/s	Yes	No	56,77
1,5m/s	No	Yes	47,47
2,0 m/s	Yes	Yes	66,02
2,0 m/s	No	Yes	84,46

Secondly, simulations were done to assess the effects of using fairing. Results brought in Table 7.1 confirm that by implementing a simple wet hull to cover the open cavities between the modules of the CROV, significant reduction in drag force can be achieved. Simulations with and without fairing were done with both 1,5 m/s and 2 m/s fluid speeds. In both cases, the results show roughly 20 % decline in drag force when fairing is used.

CFD simulation results confirm, that the drag force exerted on the hull of the prototype will be the least when both the hemispherical endcap and fairing are used. This data can be further used to find suitable thrusters, according to the speed that the CROV has to be able to reach. As specified in the design criteria, the top speed was established at 2 m/s. Therefore, in order to reach that speed, the two horizontal thrusters combined must generate at least 66,02 N of thrust. Although, if a top speed of 1,5 m/s would be considered sufficient, only 38,48 N of thrust would be needed.

7.3 Conclusion

In this chapter, a preliminary mechanical design was proposed. The structural simulation confirms the suitability of the chosen dry compartment solution. CFD analysis results showed that fairing should be used on the CROV, wherever economically reasonable, and that seemingly small hydrodynamic improvements can have substantial effect on the thrust requirement.

8. SUMMARY

As a result of this work, the design concept of a consumer-oriented remotely operated underwater vehicle (CROV) has been developed. A holistic approach was taken to analyse all necessary aspects of a CROV.

Market analysis of the growing market of CROVs was done, existing solutions were compared and analysed. This data was used to develop a set of design criteria that any prospective CROV should comply with, in order to be competitive in the market.

Based on these criteria, all necessary technical aspects were discussed, forming a design concept of the CROV. The significance of the developed criteria and concept lies in the fact that these could be used as a comprehensive framework for designing CROV solutions in the future.

Further, based on the developed concept, the mechanical design of a CROV prototype was designed. The flexibility of the resulting mechanical solution can be considered remarkable as well, because the structural solutions that are used could be applied to other submersible vehicles aside from CROVs. Future work would include building a real prototype based on the proposed mechanical design and developing an electrical circuit design based on the concept.

In general, the author would consider the work done a success, as all of the critical topics concerning the CROV were covered in this thesis and so, the possibility to use this thesis as a framework for designing CROVs, is present.

9. KOKKUVÕTE

Käesoleva töö tulemusena on välja töötatud tavakasutajale mõeldud mehitamata allveesõiduki (TAVS) kontseptsioon. Teemat on käsitletud terviklikult, et luua ülevaade TAVS kõigist olulistest aspektidest.

Esmalt on töös tehtud turu-uuring, et analüüsida olemasolevaid TAVS lahendusi. Saadud tulemusi kasutatakse töös edaspidi, et luua TAVS kriteeriumite kogumik, millele uued TAVS lahendused peaksid vastama, et olla turul konkurentsivõimelised.

Nende kriteeriumite põhjal on uuritud erinevaid tehnilisi aspekte, luues niiviisi TAVS kontseptsiooni. Töö käigus arendatud kriteeriumite ja kontseptsiooni olulisus seisneb selles, et neid on hiljem võimalik kasutada üldise raamisitikuna reaalsete TAVS lahenduste loomisel.

Lisaks on loodud TAVS prototüübi mehaanika lahendus. Saadud uudset lahendust võib pidada märkimisväärseks, sest selles käsitletud struktuurilahendused on universaalselt sobilikud ka teist tüüpi mehitamata allveesõidukite tarbeks. Edaspidises töös oleks tarvis ehitada saadud lahenduse põhjal reaalne prototüüp ja elektroonika kontseptsiooni põhjal töötada välja elektriskeemid.

Üldiselt on autor rahul töös saavutatud tulemustega, sest kõik olulised TAVS süsteeme puudutavad teemad on saadud töös kaasatud. Seega on reaalselt võimalik käesolevat tööd kasutada raamistikuna uute TAVS süsteemide loomisel.

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11. APPENDICES

11.1 Appendix 1

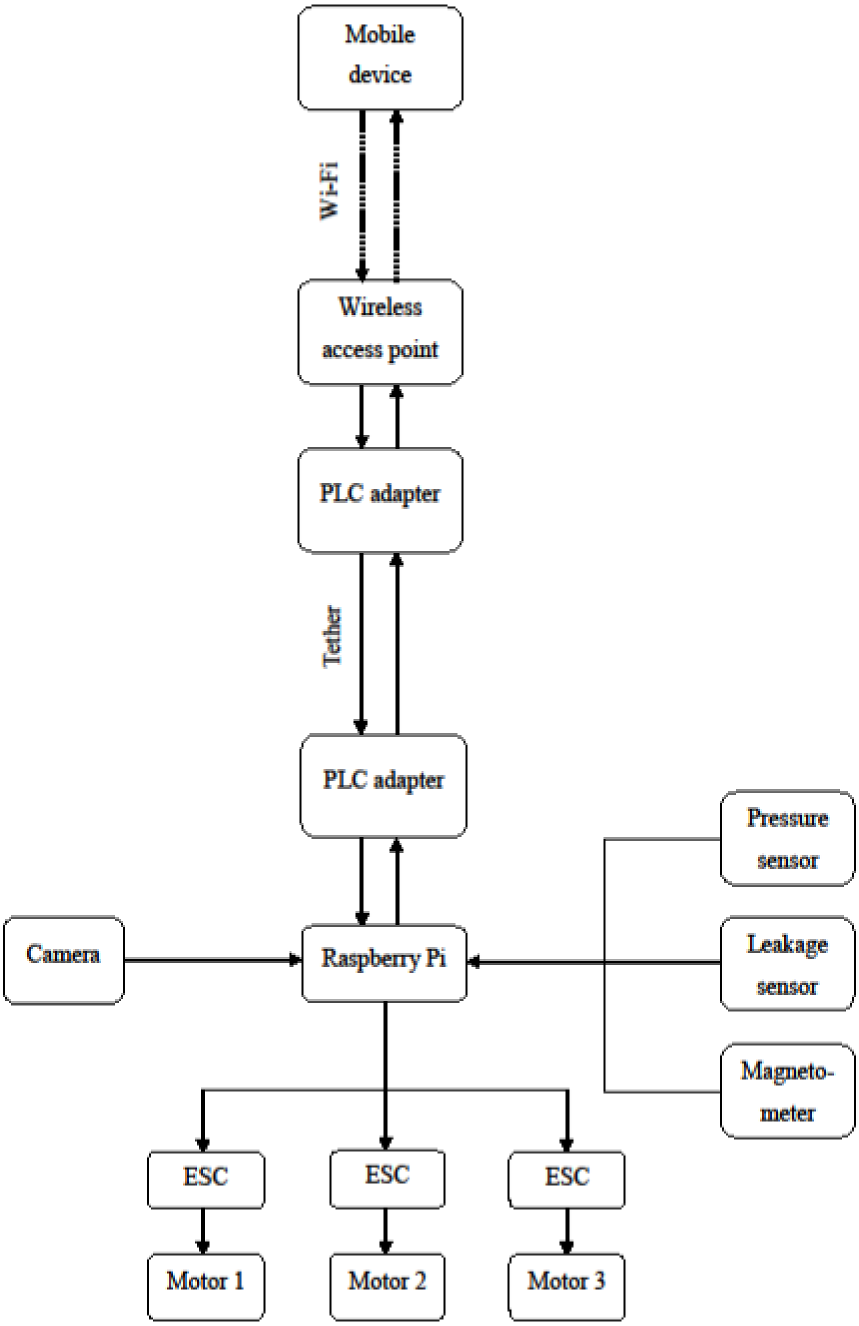

Figure 11.1. Conceptual schematic of the CROV electronics.

11.2 Appendix 2

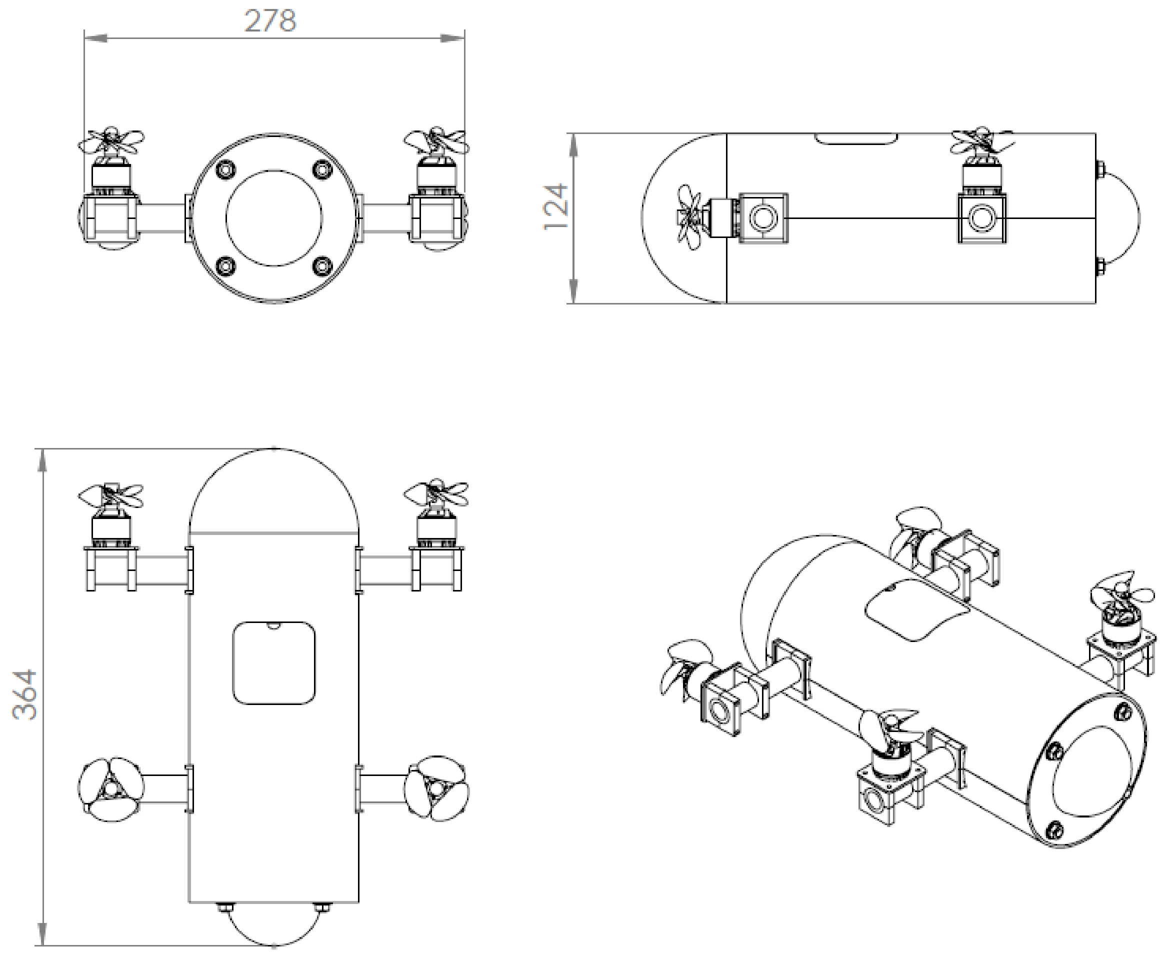

Figure 11.2. Drawing views of the proposed design with outer dimensions.