TAMPEREEN TEKNILLINEN YLIOPISTO
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DEPTH CONTROL SYSTEM ON AN AUTONOMOUS MINIATURE ROBOTIC SUBMARINE

Master of Science Thesis

Examiner: Professor Kari T. Koskinen
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ABSTRACT

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There are tens of thousands of flooded mines in Europe, which of majority has unknown areas that cannot be searched by divers. A robot must be developed in order to examine the mines and decide about reopening them. This robot has to be autonomous, and able to navigate through the narrow tunnels and shafts. Its propulsion system is a crucial part of exploring the mines. The robot being a submarine, it should also be able to adjust its buoyancy. These two systems allow for the vertical movement of the submarine, propulsion system being the only means to move horizontally. This thesis is focused on the vertical control systems, and the challenges the required very small size will create. It is worth mentioning that a similar robotic submarine has not been developed earlier, which makes the project interesting.

In this thesis, first, some basic principles of submarine diving and its depth control methods are explained and different ballast system operating principles are compared and explained. The propulsion system is tested, its performance is evaluated and different methods for usage of thrusters is studied. The submarine should have four thrusters on both sides in a manifold that is integrated to the hull, in order to maintain spherical shape. Two horizontal ones on each side, for dependability, and two vertical ones as well. The energy efficient way is to move slowly and avoid active braking.

The buoyancy control system is the more complex of the two vertical control systems. Considering many different options, the most suitable system for this robot shall have a small brushless electric motor, micro-hydraulic pump, shutoff valve and ballast cylinders that are used to control the weight of the submarine. The system will use oil as the media instead of water, because of issues with availability and size of water hydraulic components.

The power consumption of these two systems was measured in case of thrusters and simulated in case of buoyancy control and a guideline when to use one or the other was formed. The buoyancy control is less energy-efficient than it could, mostly because of the low efficiency of the small gear-type pump. The system would be greatly improved if the pump could be replaced with a more efficient one.

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Euroopassa on kymmeniä tuhansia hylättyjä, vedellä täyttyneitä kaivoksia, joista suurimmassa osassa on tutkimattomia ja sukeltajille saavuttamattomia alueita. Mahdollisesta uudelleenkäyttöönotosta päättämiseksi tarvitaan robotti tutkimaan nämä kaivokset. Sen täytyy olla itsenäinen ja kyetä kulkemaan kapeiden tunnelien ja käytävien läpi. Propulsiojärjestelmä on elintärkeä osa tätä tutkimustehtävää, ja sukellusveneen ollessa kyseessä myös kelluntavoiman säätö on tarpeellinen. Nämä kaksi järjestelmää mahdollistavat korkeussuuntaiset liikkeet, ja tämän työn painopiste on niiden suunnittelussa ja kokorajoitteen asettamissa haasteissa. Maininnan arvoista on myös se, että tämänkaltaista sukellusrobottia ei ole aikaisemmin tehty, mikä tekee hankkeesta erityisen kiinnostavan.

Aluksi käydään läpi pääperiaatteita sukellustavoista ja tutustutaan erilaisiin painolasti- ja tilavuudensäätöjärjestelmiin. Propulsiojärjestelmälle tehdään suorituskykymittauksia ja tutkitaan eri tapoja käyttää järjestelmää tehokkaasti. Robottisukellusveneeseen tulee neljä potkuriyksikköä molemmille sivuille putkiristikkoihin, jotka pallomaisen muodon säilyttämiseksi upotetaan laitteen runkoon. Yksiköitä tulee kaks vaakasuuntaista yhtä putkiristikkoa kohti luotettavuuden takaamiseksi, ja myös kaksi pystysuuntaista yksikköä. Energiatehokkainta on liikkua rauhallisesti ja välttää jarruttamista moottoreita hyödyntäen.

Järjestelmistä monimutkaisempi on painolastijärjestelmä, jonka toteuttamiselle useista vaihtoehdoista sopivin kokonaisuus on käyttää pienen harjattoman sähkömoottorin pyörittämää pienoishydraulipumppua, sulkuventtiiliä ja painolastisylintereitä, joilla säädetään aluksen painoa. Väliaineena järjestelmässä käytetään öljyä, koska vesihydraulisten komponenttien koko ja saatavuus eivät mahdollista niiden käyttöä tässä sovelluksessa.

Järjestelmien virrankulutuksia määritettiin propulsiojärjestelmän tapauksessa mittaamalla ja tilavuudensäätöjärjestelmän tapauksessa simuloimalla, ja tuloksista muodostettiin suuntaviivat siihen, millaisissa tilanteissa kumpaakin kannattaa käyttää. Tilavuudensäätöjärjestelmän hyötysuhde on huonompi kuin se voisi olla, pääasiallisesti matalan hyötysuhteen omaavan ratastyyppisen pumpun ansiosta. Mikäli pumppu onnistuttaisiin korvaamaan toisen tyyppisellä, järjestelmän suorituskykyä voitaisiin parantaa olennaisesti.

PREFACE

This Master's thesis has been carried out in the Department of Mechanical Engineen and Industrial Systems at Tampere University of Technology.

I'm willing to express my gratitude and appreciation for the project manager of the department and supervisor of this work, Jussi Aaltonen, for guidance and encouragement to finish this thesis. I also would like to thank the examiner of this thesis, professor Kari T. Koskinen for his efforts on the way to complete the work. The cheerful atmosphere among the research assistants in the department has also been helpful, thus I would like to thank all the members of our research team.

I am also grateful to my family, who have supported and pushed me to finish this thesis and finally become a Master of Science. Last, but definitely not the least, my fiancé Emma deserves special thanks for support and understanding.

Tampere, Finland, on 16th May 2017

Tuomas Salomaa

CONTENTS

TERMS, DEFINITIONS AND SYMBOLS

ROV	Remote Operated Vehicle.
AUV	Autonomous Underwater Vehicle
RC	Radio controlled
CAN (-bus)	Controller Area Network, a vehicle bus standard, allows communication of several microcontrollers as independent units
I2C	"Inter IC" bus, simple 2-wire data transfer bus for short distances
CoG	Center of Gravity
CoV	Center of Volume
BLDC	Brushless DC(-motor)

$\Delta V_{adjustable}$	Size of adjustable (ballast) volume
$\Delta F_{buoyant}$	Change in buoyant force
ΔF_{pitch}	Change in pitching force
$\Delta \tau_{ballast}$	Torque created by altering ballast volume
$\Delta C_g C_V$	Distance between CoG and CoV
ρ_{oil}	Density of oil
ρ_{water}	Density of water
x_{volume}	Distance between adjustable volume and CoV
m_{robot}	Mass of robot
V_f	Volume of fluid in chamber
V_c	Geometrical volume of chamber
q	Flow rate into the chamber
E	Fluid bulk modulus
P	Pressure

1 INTRODUCTION

The buoyancy of a submarine, whether it is scale-model or a live scale one, is based on the simple principle of the buoyant force being compared to the weight of water – or other fluid - it displaces. The difference between weight of the submarine and the weight of the water displaced defines the buoyant force. Therefore, to achieve capability to adjust the buoyant force, it is necessary to adjust the volume or weight of the submarine. This kind of depth control by adjusting buoyancy is called static diving. There is also another way to control the depth of the vessel, it is called dynamic diving, which means fins or separate propellers used only for vertical motion control the depth of the submarine. The principal idea is to adjust the speed of the submarine or the angle of the fins to create a negative buoyant force to overcome the slightly positive buoyancy. This however requires continuous movement of the vessel in order to maintain depth. (1)

1.1 Scope of the thesis

The basis for this work was to introduce various methods of submarine vertical control systems and their working principles. Another key part is to describe the design process of the mechanical parts of the depth control system for a robotic submarine, but it will also introduce the propulsion system, some of its specifications and measurements and also discuss different operating situations where using one or another of these would be beneficial. There are various solutions used for controlling the buoyancy on scale submarines, but this application has some very specific requirements and limitations, so the process will be unique. The defining of the requirements and limitations is the first challenge to tackle. Eventually the different ways to control vertical movement should be compared by different viewpoints, like accuracy, efficiency and motion dynamics.

1.2 Dynamic diving

Dynamic diving requires continuous forward motion of the submarine and thus it has a limited angle of descent unless the submarine can be pitched to 90-degree angle. On the other hand, it is simple to control and it is very responsive. Submarines always have hydroplanes in order to control the depth and angle of the vessel. Dynamic diving is also very commonly used on ROV's and AUV's, and in some cases, they use separate propellers to move the small vessels vertically. A commercial ROV, the BlueRov2 manufactured by Bluerobotics, with a pair of vertical thrusters is shown in Figure 1:Commercial ROV with vertical thrusters below (2). The vertical thrusters can be seen on both sides of the clear container.

Figure 1:Commercial ROV with vertical thrusters

This kind of solution gives the possibility to have only vertical movement while keeping the construction of the model simple; the ballast system needs space and is more complicated to build than an extra propeller for vertical motion. On the negative side is that vessels without buoyancy adjustment need to have small positive buoyancy to ensure surfacing in case of loss of power. This leads to significant energy consumption as the vessel has to maintain the horizontal velocity for the planes to create enough descending force to overcome the buoyancy and create a descending velocity, or alternatively use the vertical thrusters constantly. Even holding stationary requires continuous use of energy in case of dynamic diving, although the power needed can be quite small if the amount of positive buoyancy is small. If a separate vertical thruster is not used, a dynamic diving vessel is not able to maintain position. (3)

Dynamic diving technique is used at least as a part of vertical control in practically all vessels capable of controlled submerging. In submarines, there are adjustable fins called hydroplanes or diving planes, which are used to control the lift force. These planes are used not only to control the depth of the submarine but also to manipulate the vertical pitch. When diving, the aft ones are at first turned upwards to achieve desired decent angle, and during decent kept level. A moment before the desired depth is reached, the fore and aft planes are used to level the submarine

1.3 Static diving

Static diving means controlling depth without using propulsion, it is executed by altering the buoyancy as mentioned earlier, and all submarines are equipped with ballast control systems along with the hydroplanes. This is to say that live scale submarines use both ways of controlling their depth, buoyancy is controlled by the ballast system and the fine-tuning of depth is done using the hydroplanes. Controlling the volume of the submarine is practically never used, controlling the weight by taking in or forcing out water is the method used on most submarines. Although one could question the difference between these two, when taking in water the volume of the submarine is reduced, thus letting the water in to increase the weight of the submarine.

Typically, a live scale submarine is trimmed just slightly positive in buoyancy and the depth is controlled by the hydroplanes, so that in case of a power shutdown the boat eventually surfaces. This is due to safety reasons, if the control is lost and the submarine surfaces, there is a chance of survival, even it might be low in wartime situation. If the buoyancy was negative and control of submarine is lost, it will sink to bottom of the ocean and in many places that will create more pressure than the submarine can handle, leading to leak or destruction of the hull and drowning of the crew. For short periods of time also negative buoyancy can be used for rapid submerging, for example when being under attack from surface, but after the desired depth is achieved the buoyancy is returned to slightly positive. The ballast system is also used to assist the dynamic diving; there are separate smaller tanks, so called trim tanks, which are used to adjust the vertical heading of the submarine. This means that live scale submarines are able to statically dive, but in most situations they actually are slightly positively buoyant and dive dynamically. (4)

1.4 Different ballast system types

Ballast tanks are used for different purposes in submarines, but they can also be roughly divided to three different types by their working principle. By purpose there are multiple different groups, but their working principles are the same regardless of the purpose being to control depth or heading, or work as an emergency backup.

Perhaps the simplest solutions are amongst mechanical type ballast tanks, they can be piston-operated cylindrical type or membrane-type ones. These tanks are controlled mechanically by moving a piston or by controlling the space a membrane or bladder is allowed to fill. This kind of solution often requires significant amount of space for the control mechanisms and thus mechanical tanks are not commonly used in live scale or model submarines as space is often limited. The benefits of mechanical type tanks are the easy and precise operation using, for example, a linear actuator that moves a cylinder or a membrane. The lack of air that could compress allows a mechanical ballast system to achieve very precise and constant values of buoyant force. The only flexing of the system comes from the possible membrane and the mechanical parts themselves. An illustration of mechanical piston type ballast system below.

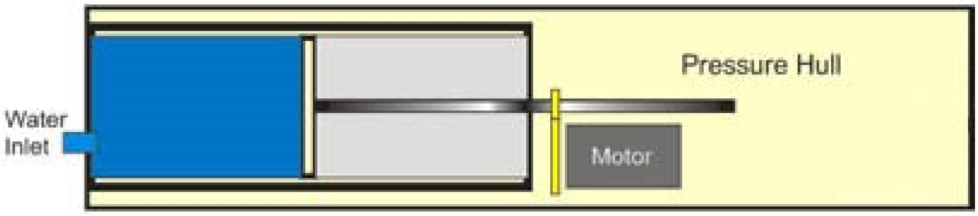

Figure 2: Piston-type ballast system (5)

Pump controlled systems are the second group, pump controlled systems can have either solid or flexible tanks, in case of a fixed volume tank it will be a pressurizing tank which is filled and drained by a pump and has no other connections. This kind of tank is filled with air in atmospherical pressure, and when submerging the pump forces water into the tank causing pressure in the tank. This has the advantage of being able to empty the ballast tank, at least partially, just by opening a valve instead of running a pump to drain the tank; this might help in case of running very low on power. This however might not be very likely situation with a submarine but a scale model. The is also another option of a variable size tank, in other words some form of a bladder, which is filled through a valve and drained by a pump. Bladder type tank can be also controlled mechanically as stated in previous chapter. Pump controlled tanks are also very precise and they can hold constant buoyant force due to the valve that closes the flowpath into the tank. A pump controlled system can also be combined with gas operated systems, for example an emergency blow using compressed air is possible. (6)

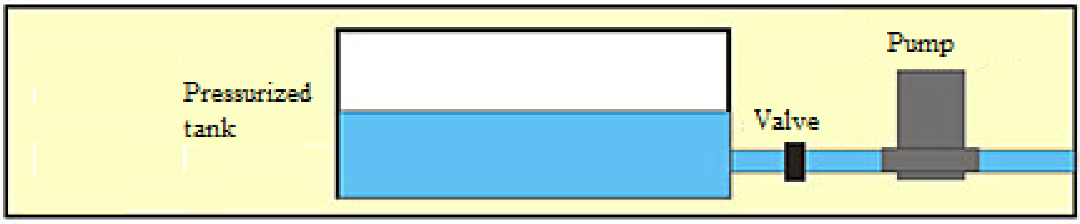

Figure 3: Pressurized tank system

The third type is gas operated tanks, which are the type used in submarines. Gas operated tanks are most difficult to control, because gases contract so defining the exact volume is difficult. If the depth is changed 20%, also the volume of air in the ballast tank changes by 20%, which causes the buoyancy to change, creating need for constant adjustment of the buoyancy when using gas operated ballast tanks. That is why gas operated tanks are usually used completely filled or completely dry, and there are several small tanks to create the wanted amount of buoyancy. It is also possible to mix these groups, for example a pump controlled fixed tank can be equipped with a gas backup system so it can be blown empty in case of a pump failure or some other kind of emergency. (1)

Typically ballast tanks in submarines are used not only for adjusting buoyancy, but there are also separate emergency dive tanks, which are filled only when the submarine must dive as fast as possible, for example to evade enemy attack. Some smaller ballast tanks are used to trim the pitch of the submarine, and there are also backup trim tanks in case the submarine is damaged and the tower is lost. (4)

2 REQUIREMENTS AND CONDITIONS FOR VERTICAL CONTROL SYSTEM

Submarine buoyancy control systems are quite varying and there are plenty of different ways to control the depth of a submarine. This work will now concentrate on the design process of the depth control system for a specific AUV. It is a 60cm diameter spherical shaped submarine intended for use in exploring and mapping flooded mines. The AUV has to be able to operate in depths of five hundred meters and be able to move upright vertically, which requires possibility to dive statically, i.e. to use some kind of ballast system or alternatively vertical thrusters. Vertical thruster would enable the AUV to move upright vertically, but diving to five hundred meters using only thrusters would take a significant amount of battery power. This leads to the conclusion that a ballast system is considered beneficial.

2.1 Requirement specifications for propulsion and ballast systems

Ability to explore centuries old mines is the primary object for this entire design process, and it is followed by one strict limitation that will create several challenges: size. Especially in the past mines were made so that the passageways were very cramped and narrow, because only handtools were available. That is why all the passages are only just as wide as they have to, and the robotic submarine has to get through these passages. In addition, some of the passages may today be collapsed so the AUV has to be able to turn around and at all situations, avoid being stuck. There is no way to communicate with the AUV in deep parts of the mines; therefore, the autonomous operation is a necessity. These things combined with a requirement of reliability and a minimum of 5 hours of battery-powered operating time create strict restrictions on many structures, including buoyancy control system.

Weight is one of the things to be concerned, but it is not as crucial as other restrictions. The total buoyancy for the vessel is about 100kg, so the weight of buoyancy control system probably is not the most important priority. Avoiding any unnecessary parts and keeping system as small as possible are the initial means of keeping the size reasonable, and it also helps keep the weight low.

Space is definitely a high priority design objective in the robotic submarine in question, there is very limited space inside the spherical hull which has outer diameter of 60cm, and many scientific instruments and batteries should also fit in. This means that the size must be kept at absolute minimum. Keeping the controllable volume as small as possible within the requirements and using as small components as they are available are the reasonable ways to minimize the needed space.

Speed is not that important in this matter, the mission of the robot is to create a map of the mines explored and the robot should thus move calmly regardless of the buoyancy system. The initial requirement for horizontal velocity is two kilometers per hour and there is no specification on vertical velocity. Therefore, it seems reasonable that we can have slower speed in vertical motion than horizontal motion, which allows smaller controllable volume to be used to save space and power.

Position of the ballast system inside the submarine is also something to be considered in the development process, as it is required that the submarine is capable of pitching ninety degrees either up- or downwards. If the desired structure is oil-containing bladder that will be filled or drained according to the need of buoyancy, it shall work also when the submarine is pitched. This creates a need for a special oil reservoir that should be able to feed the pump regardless of the position of the submarine.

The media, water, is also something to be considered, as we do not know exactly the quality of water in the mines. Therefore, it is necessary to be prepared for salty, perhaps even mildly acid water. This is a problem especially if we end up using a system that pumps the water from the mine to the ballast tank and back, and regardless of the adjustable volume structure there

Besides ability to control its volume and thus buoyancy, the submarine must of course be able to move in the mines with sensible speed and on the other hand without using too much energy. The propulsion system is a serious challenge, as the small size combined with fairly high pressure requirement limits the options for thrusters to barely none, usually equipment used in deep sea diving is bigger and therefore the thrusters are significantly bigger than what would be suitable for this project. Besides as small size as possible and low power consumption also reliability is vitally important for the robot.

Numerical specifications for the thruster system were maximum speed of 2km/h and maximum operating depth 500m, other performance requirements are to be reasoned within the space and efficiency factors.

3 DESIGN OF PROPULSION SYSTEM

As space is very limited and the shape of the submarine hull should be kept as spherical as possible it is not possible to place the thrusters outside the hull even it would increase the efficiency and controllability. On the other hand, the requirement to place the thrusters inside the hull in tubes takes up valuable space, which will be required also for the batteries. And the more energy propulsion system uses the more batteries have to be taken along, which is why the efficiency of the thrusters is very important. They will probably be one of the most energy consuming equipment and thus have a significant effect on the amount of batteries needed.

Due to the limitations in size and pressure, there really was one suitable option for this application, which was the Bluerobotics T200 (7). The option with the speed controller attached to the thruster itself was chosen in order to save space inside the hull and reduce heat production in the hull, and there was a nice bonus that the integrated speed controllers can be networked together and controlled via I2C bus.

The requirements rule out many ideas to place the thrusters, and after thorough brainstorming a pair of intersecting pipes on both sides of the hull was seen as the most promising construction. There should be two thrusters in horizontal pipe as well as vertical pipe in order to have better reliability and extra power in reserve for surprising situations. The dependability should be increased by having two thrusters in each flowpath, so if one thruster is inoperational, the robot would be able to return to base for repairs.

To find out more about the performance characteristics of the thrusters a test bench was built so that the produced force of the thrusters could be measured accurately with different combinations of control values. The thruster’s integrated speed controllers communicate via I2C bus, and they give out data on current and voltage to the bus, giving the opportunity to calculate efficiency relatively easily. The thrusters were placed in a cross-shaped combination of pipes made out of plastic sewer pipe. There was also a fifth flowpath in this cross-section to test if a sway motion would be possible, and the whole assembly was placed in a water container. In the upper part of the test rig, a strain gage cell was attached to the boom which holds the thruster assembly in order to define the force produced by the thrusters. There is a picture of the testbench set-up below.

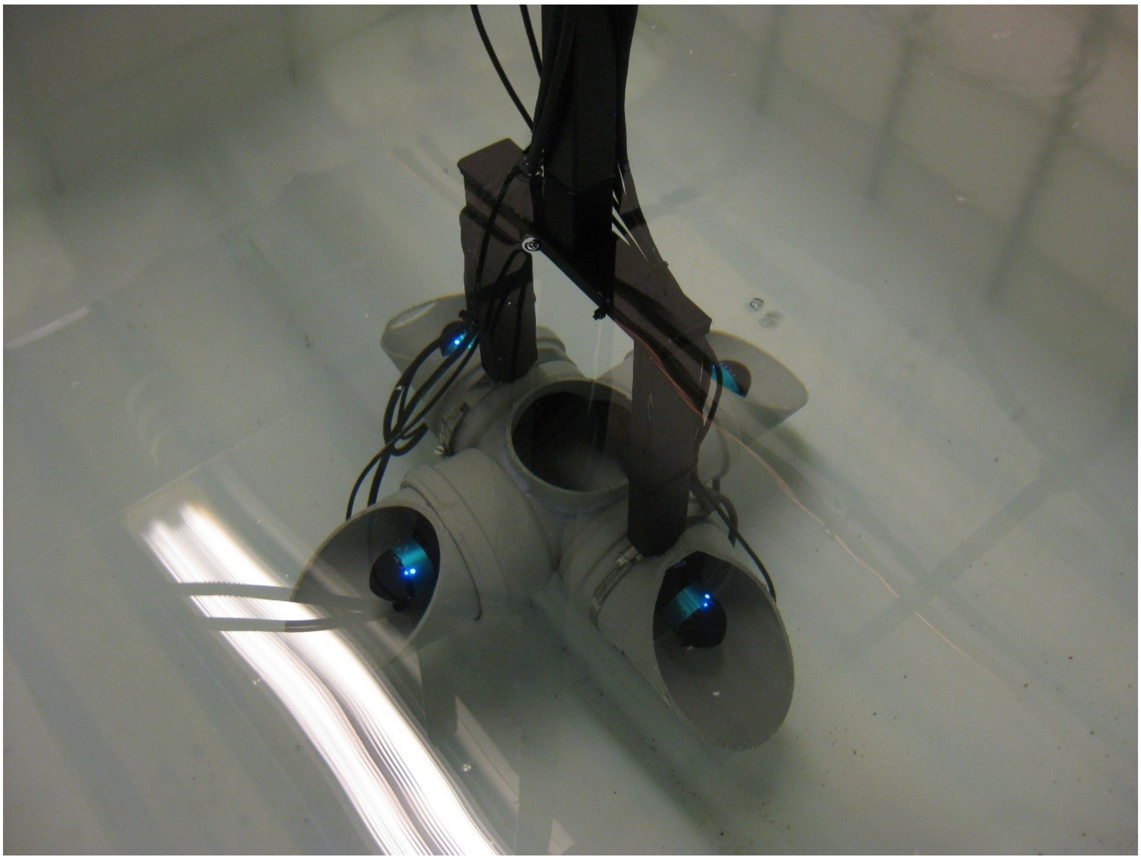

Figure 4: Thrusters in testbench

3.1 Propulsion system test rig and testing

First negative observations on the thrusters were done before any of them had rotated a single revolution; the plastic shell does feel a bit toy-like, and the mounting points for the thruster have tiny cracks in every unit. More negative remarks were discovered when the thrusters were powered up; not all of them initialize properly every time the I2C bus and thrusters are powered up, regardless of the order of powering these. Some thrusters initialize always properly, and some are always causing delay by taking several minutes to initialize. Figure 5: Cracks around thruster mounting nuts demonstrates these cracks on one thruster mounting points.

Figure 5: Cracks around thruster mounting nuts

The cross of pipes that simulates the manifold was attached to the boom so that the desired direction of force could be measured: there was only one force cell and the position of the cross was easily altered so that vertical, horizontal and even sway force could be measured. There were some crucial things needed to know about the behavior of the thruster setup, and some of the big amount of test data was just to confirm different assumptions. The tests were performed by altering the power of each thruster in ten percent steps and measuring the steady-state force.

The current of the thrusters was measured by the speed controller integrated to the thruster, and this data was transferred via I2C-bus to the bus controller and on to the computer. The current measurement of the integrated speed controller prove out not to be very accurate on low power situations, when the control was about a quarter or less of maximum power. For comparison the current was also measured with a separate current meter and compared to the reading of the speed controller. The force was measured in many various situations, including cross-flow situations where all thrusters were run at the same time simulating a situation where it is desired to move horizontally and vertically at the same time. It was also tested if a sway force was created when running the thrusters in the same pipe at different speeds, or even so that one was pushing the submarine forwards and the others pushing water towards the intersection of all the pipes in order to create sway force or at slower speed just feeding water to the thruster pushing the submarine forward.

The direction the thrusters were pointing was also turned around, and a thruster tested outside the manifold to get a comparable result which can be compared to the performance achieved when the thrusters are in the manifold and on the other hand also the manufacturer announcement. Clockwise and counterclockwise rotating propellers and even a 3D-printed one with reversed flow direction was tested. To save some space inside the hull also a flattened pipe for the vertical thrusters was made and tested to see if shaping the pipe reduces performance of the thrusters. The chart of the different direction propellers below, and flat pipe and the reverse-flow propeller results after it.

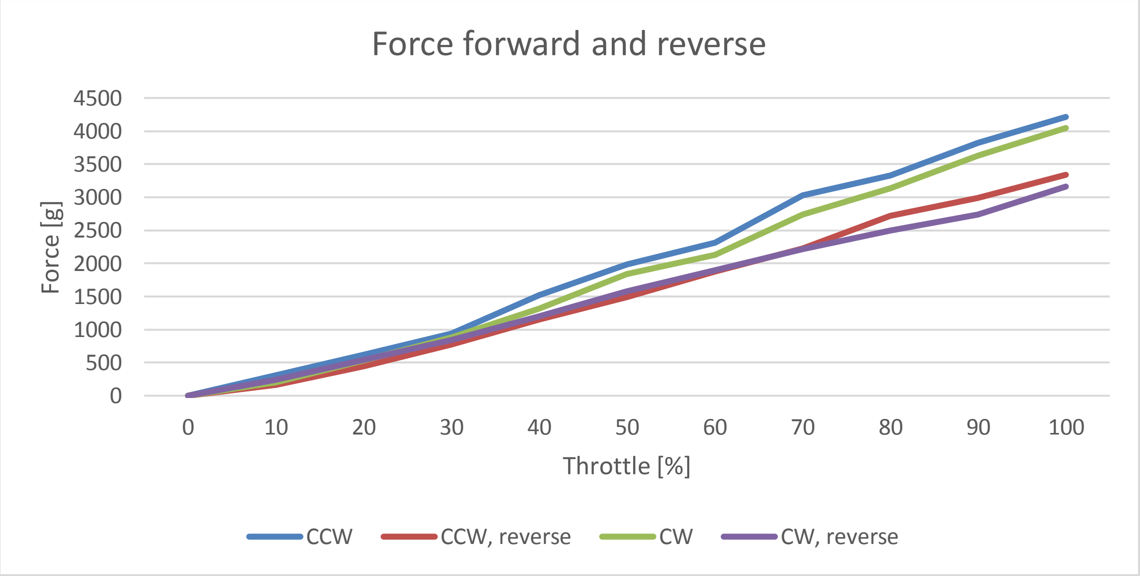

Chart 1: The Effect of flow direction

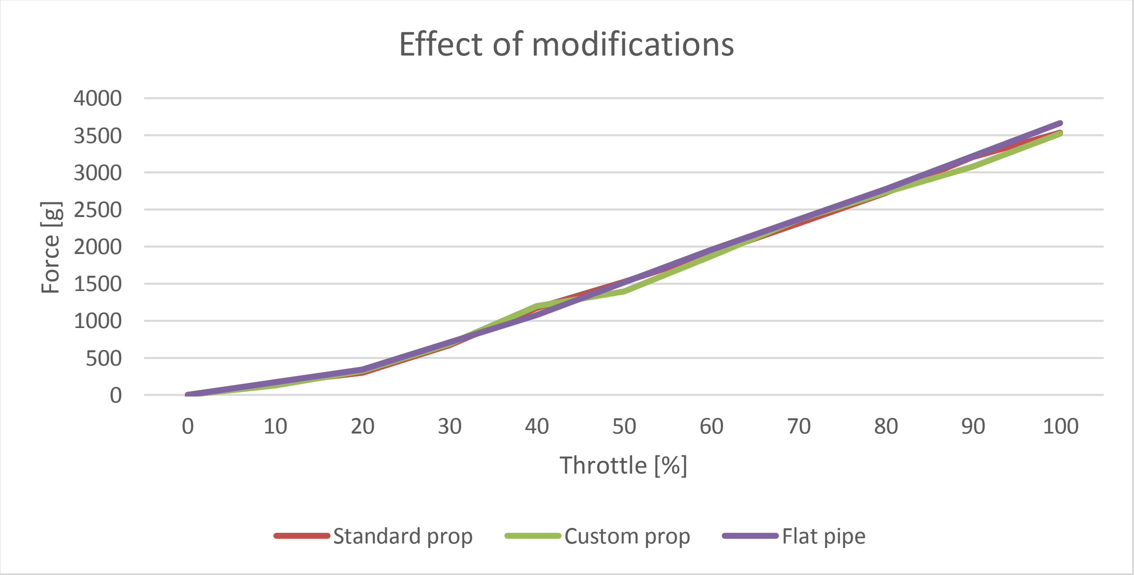

Chart 2: Effect of modifications

The custom propeller was tested in order to find out if the shape of the thruster itself would make the difference in thruster efficiency depending on the direction of force. Below there is a comparing picture of the custom reverse flow propeller and the stock one, reverse flowing on left and stock one on right.

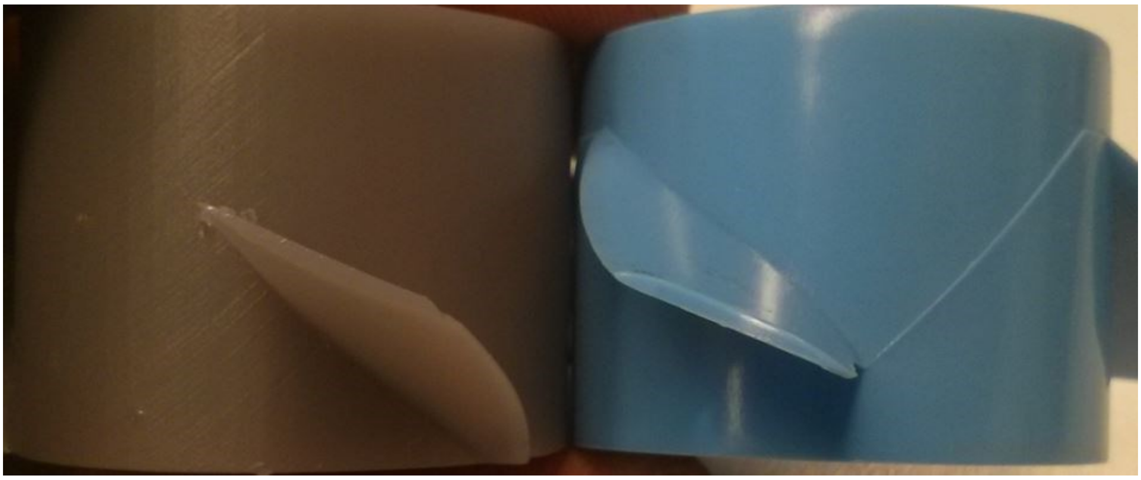

Figure 6: Reverse-flow propeller and stock one compared

The main purpose for the tests was to find out energy-efficient way to use the thrusters, and to find out more about ways to produce a certain amount of force, different power distributions between the foremost and the rearmost thruster were tested. The resulting force with one or both thruster running at same power below. Both thrusters used practically the same amount of power when running only one thruster, in case of both thrusters running the power consumption of one thruster was approximately 10% less than when the thruster was running on its own.

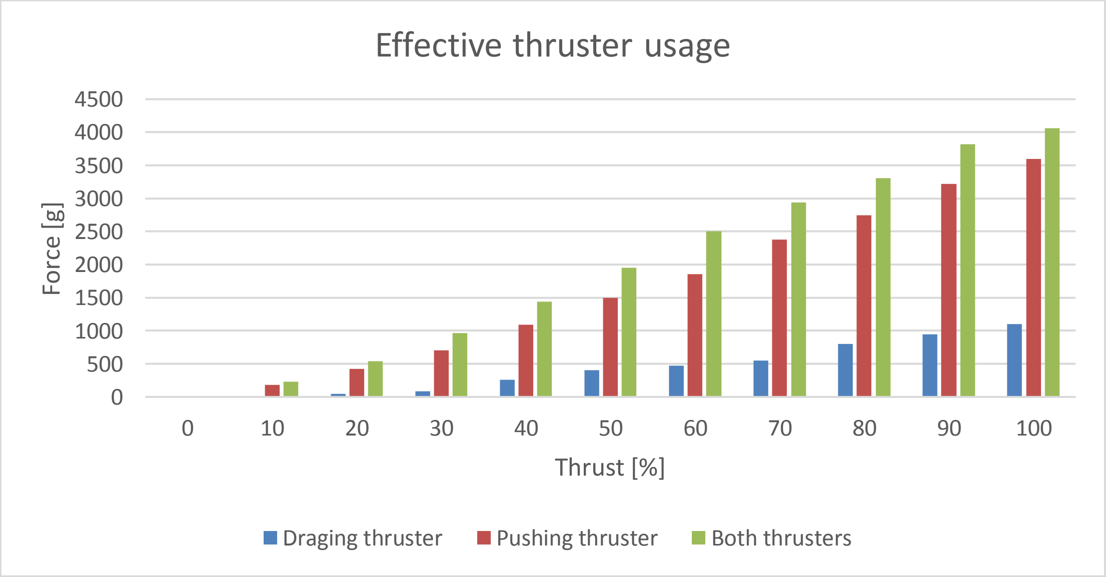

Chart 3: Using thrusters efficiently

Because of limited space, the thrusters should be placed as close to each other as possible. However, when placing them very close to the intersecting area in the middle of manifold, it was realized that the end cones of the thrusters create significant loss in efficiency when they interfere the flow in the intersecting area.

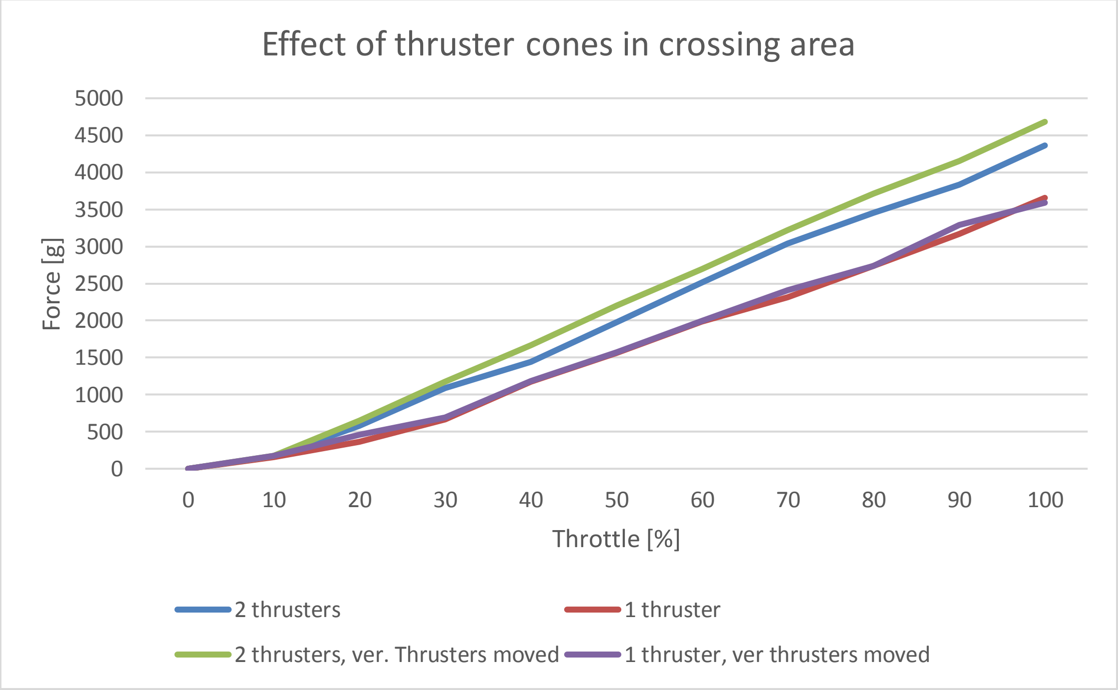

Chart 4: The effect of thruster cones in intersection area of manifold

3.2 Discussion about laboratory tests

When the actual tests begun, it was a positive surprise to notice that a thruster that is not placed in the manifold but a single metal beam actually has more power than the manufacturer advertises, and even when placed in the manifold it performs really close to what is promised. This is when the thruster is installed the propeller outwards from the manifold, which causes the thruster nose cone to protrude the intersection area of the pipes. The direction of the flow through the thruster seemed to be the significant matter what comes to created force. Manufacturer provides clockwise and counterclockwise propellers for every thruster, but they are clearly meant to be pushing in the same way, only rotating in different directions. After noticing that the direction of flow makes a significant difference in the force and efficiency of the thruster they were placed so that there were two thrusters pointing the same direction presenting horizontal thrusters pointing forwards, and other two were opposite to each other presenting vertical thrusters. This setup was used in the results discussed in this chapter as it gave significantly more efficiency when going forwards, which is the preferred way for the submarine to move, and reverse thrust should be used only when braking or turning stationary. In previous chapter, there is Chart 1: The Effect of flow direction clarifying the differences between flow directions and rotation direction, where it is easily seen that clockwise and counter-clockwise propellers have very similar results, and both have significantly worse results when the flow direction is reversed. It also seems that the counter-clockwise propeller produces a little bit more force in either direction, which may be due to production tolerances. The revolutionary speed of the propeller was the same with both propellers, meaning that the difference is the propeller and not the electric motor or it's speed controller. It was also noticed that CCW propeller actually had more thrust force when going forwards than the CW one, and less when going backwards, which would imply it is more optimized to work in only one direction. However, the manufacturer states the only difference is the direction of rotation, and evaluating by eye or using a caliper any differences were not found, except the propellers being mirrored.

The next interesting comparison was focused on possibilities to save space. The thruster frame is shaped so that when moving in the direction of better efficiency the propeller is in the rear of the thruster, which causes issues placing the thrusters in the manifold without the nose cone interfering the flow in the intersection part of the manifold. Thus it would be beneficial if the thrusters could be turned over without losing efficiency. This was tested by 3D printing a propeller, which had the blades turned upside down and moved a bit further in order not to collide with the nozzle structure. This propeller is shown in Figure 6: Reverse-flow propeller and stock one compared in previous chapter. In addition, the possibility to save space by using flattened - like the nozzle on a vacuum cleaner - pipes on vertical thrusters was interesting and that's why one was made for testing. The Chart 2: Effect of modifications shown in previous chapter shows that compared to straight pipe and standard propeller it doesn't have any downsides to use these reverse flow propellers or the flat-shaped pipe. This allows for more space-effective installation of the thrusters and more compact manifold, as the part of the thruster with largest diameter can be placed closer to the center of the manifold without the thruster interfering the flow in the intersecting part of manifold.

A good way to save space would be to use the integrated speed controller that was used in the tested units, but it prove out not to be very reliable and the data feedback from the controller was not accurate in all of the tested units. Even more, there probably have been many issues with these integrated speed controllers, as the company has ended manufacturing of the integrated ESC, and they only offer a ESC that is placed inside the pressure hull. This is a pity considering efforts to leave as much free space inside the hull as possible, as there seems to be no choice for ESC that can be submerged in 500m of water. This means that a suitable speed controller must be selected, tested and it has to be placed inside of the hull. A partially prototype seeming open source one, called Vedder ESC, was also tested during the thruster performance tests. It is way more complicated to configure and requires more knowledge before it is operational, but it seemed more consistently working than the integrated ones. Also it is one of very few BLDC speed controllers that have option to use Can-bus to connect the ESC's to a higher level microcontroller. The final choice of ESC is still open, but from the effectiveness viewpoint the efficiencies of these different speed controllers were equally good, and the only difference was in the way of controlling the speed controllers.

Perhaps the most important observation concerned efficiency and the most power-economical usage of horizontal thrusters; when going forwards, least power is used when running only the rearmost thruster to produce all of the required thrust while the foremost is stopped completely. As long as the required thrust is achievable using only the rearmost thruster it is least power consuming way to use only the rearmost thruster. As the Chart 3: Using thrusters efficiently in previous chapter demonstrates, the foremost thruster, which drags water to the manifold, makes drastically less force than the rear one, and even the combination of these two is not much better than the result using only the rearmost thruster. When it is taken into account that they both use very close to the same amount of power, it is obvious that using the foremost thruster should only be used when braking, reversing or turning stationary, or when the rearmost one is inoperational. That is to say, the foremost thruster is mostly a backup to add dependability of propulsion system. Dependability is one of the key elements on an autonomous submarine, and thus it seems reasonable to keep the two horizontal thrusters per side, even though most of the times the foremost one shouldn't be used.

The overall quality of the thrusters is also related to dependability, and in these tests the longevity of the thrusters was not tested by running them for extended periods of time, but some notes about the overall quality were made. Previously it was mentioned that thruster attachment points had cracks around them, Figure 5: Cracks around thruster mounting nuts shows the cracks. By visual examination, the cracks did not enlarge during the tests, and the issue probably is more cosmetical than a serious structural problem. The nuts did stay in place during several installations and uninstallations of the thrusters, and any movement between the nut and thruster frame was not noticed. The cracks anyhow do give a slightly negative image of the quality of these thrusters, regardless of the significance of the cracks. The longevity of the thrusters is not likely to be endangered by these cracks, but one of the thrusters had a cut winding connection after only some minutes of runtime. Other eight tested units did work fine, but testing the thrusters for extended periods of time shall be carried out before the design of the robot is complete.

Power saving possibilities were also studied when the vertical thrusters were moved a bit further away from the intersection in the manifold and tested if the efficiency is affected. As the Chart 4: The effect of thruster cones in intersection area of manifold in previous chapter demonstrates, the cones of vertical thrusters intruding the intersection area do not affect when running only the rearmost thruster, but when running both horizontal thrusters, they do affect. In the chart horizontal thrusters were run, using only the rearmost thruster or both horizontal thrusters at the same throttle command. First the test was done with the vertical thrusters installed so that their nose cones interfere the crossing area about 20mm, and for the second test they were moved about 40mm further from the intersection. Desirably only the rearmost ones are used when going forwards. When using only one thruster per manifold, it seems not to be any significant issue if the thrusters are partially in the crossing area of the manifold pipes. Previously it was tested that by manufacturing a propeller with mirrored blades it is possible to turn the thrusters around while maintaining the efficiency. The difference made in efficiency by turning the thrusters around is smaller than could be expected, but it still seems worth executing. When combining the benefits of being able to move the thrusters out of the intersecting area of manifold pipes and maintain the efficiency while being able to make more compact manifold the modification seems very reasonable.

The possibility to create sway force was also tested with a vast amount of different throttle combinations, and there were really three significant observations worth mentioning about the sway force. First it seems that in order to create a sway force all of the thrusters need to be pushing water into the crossing of the pipes. That is to say, the maximum achievable sway force when moving horizontally or vertically is practically nothing. It would sound reasonable that if three thrusters push water into the crossing and one pushes water out of there it would still create a sideways force, but according to the measurements this is not the case.

The second notice is probably not surprising, but it was noticed that the efficiency in sway force production was very bad; all thrusters at full power resulted in a sway force of 4.2kg, which is roughly one third more than the force only one thruster produces in its designed flow direction. That leads to conclusion that sway motion should only be used in short distances and only if it eliminates the need to rotate the submarine. The third notice was even less of a surprise: it is impossible with this setup to pull water through the side of the manifold in order to create sway force in opposite direction. When all the thrusters were trying to pull water from the intersection all that was produced was major turbulence and nasty sound, which was assumed as cavitation, but no measurable force was achieved.

4 DESIGN OF BUOYANCY CONTROL SYSTEM

Buoyancy control system is simply a system that controls either the volume of the vessel or the weight of the vessel. In this application, the system has to be very compact size and very dependable. The simplest construction would be a container for fluid or gas, whichever shall be evaluated more suitable, a pump and motor in case of fluid, a shut-off-valve for the adjustable volume, and the adjustable volume that works as the actuator. If oil and thus a pump shall be used, there also should be a pressure relief valve to protect the components from too high pressure in case of a non-expected situation.

The adjustable volume was supposed to be kept as small as possible, so the conclusion was to aim for capability to have 1kg worth of negative or positive buoyancy at any situation. That means there should be capability to compensate for the compression of the hull and the change in water density. Approximate FE-analyses on the hull compression for this project had been made, and for the change in radius at 50bar pressure was estimated value of 0.48mm. Thus, we have the volume change due to compressing of the hull at a bit more than half a liter.

The density of the water changes as a function of temperature, and we do not know exactly the temperatures we can face at the mines. Assuming that the temperature will stay between freezing point and +30 Celsius, the change in water density is approximately half a percent. (8) The volume of the submarine is about 113L, so the volume needed to compensate the change of water density is a bit more than half a liter. Thus the total compensation volume needs to be about one liter, and the buoyancy ought to be one kilo in either direction, so total adjustable volume of three liters is necessary.

4.1 Media and adjustable volume for buoyancy control system

The first few ideas that came up as possibilities to use as buoyancy control systems were some kind of high pressure gas container and a ballast tank with fill and blow valves, and a pump-controlled ballast tank filled with water. After brief consideration the idea of gas was abandoned, because it would be a limited supply and we need 5 hours of continuous operating time, we should not use a buoyancy control system that has a power source of its own that can be depleted before the main power source needs to be charged. Another good reason not to use gas for controlling the buoyancy is the compression ratio of it; it contracts very much under pressure so maintaining neutral buoyancy would need more continuous control than it would when using water or some other non-compressible fluid.

This need for continuous control leads back to the issue of running out of gas because the buoyancy is more often altered. In addition, altering the ballast volume towards less buoyancy releases gas bubbles to the mine, which might cause some silt or other debris to break away from the roof of the tunnel and that is not desired, because it may reduce the visibility significantly, and thus make mapping of the mine more difficult. These issues with gas state the need to use fluid as media for buoyancy control instead of gas.

Pump-controlled ballast tank would be more easily controllable system, but we need to keep in mind the limitation on size and weight; it seems there are no off-the-shelf micro hydraulic pumps that can withstand water in any form, salty or not. Water-hydraulic pumps capable of 50bar seem to be excessively big and heavy to be fitted in the submarine in question, and making an own unique micro-water-hydraulic pump is not the desired solution. It would definitely be worth studying if a physically small water-hydraulic pump was available, as it would reduce the number of parts for the ballast system and thus save lots of space. Presumably closest to a suitable pump was one that is close to being suitable for this application, Water Hydraulics P1 (9), which was fairly reasonably sized and had the capability to provide sufficient flow rate and way more pressure than necessary. The reasons that made this pump not very suitable for the application: it was not reversible, which means a directional valve would be required in order to be able to both fill and drain the ballast tank. The pump also had very high requirements for the purity of water, which would require good filtering of the water.

The problem with having a unidirectional pump is that the directional valve for water is actually significantly bigger than the pump, too big to be fitted in the robot. The same issue applies to the filter, to achieve the required purity level of water for the pump it would require use of a substantial sized filter unit, which again ruins the idea of saving space by leaving out the bladder and using water as the ballast load. When all these aspects are considered, the most suitable option is to use a pump-controlled system that utilizes oil of some sort.

Mechanically operated cylinder is another option, and it actually has some significant advantages over the systems pondered about previously, i.e. its position and thus volume can be easily and exactly measured, there are quite few moving parts and it is easily adjustable in steps of any size. Shame that the mechanism needed for a cylinder of 4 liters' volume combined with the cylinder takes very much space, which is one the reasons this idea was discarded. Other big issue would be force as the space would limit the stroke of the cylinder and thus increase the diameter of the piston, it would create very big force to the mechanism that operates the piston and it would result in a really big and heavy mechanism, which is exactly what is not desired. The force with a cylinder of 22cm diameter and 11cm height would be 22 tons at 50bar pressure, which cannot be achieved with a mechanism of reasonable size.

Hydraulic pump-controlled system seems like the best option, and it was obvious that the micro-hydraulic pump would have to use some kind of oil as its medium and a membrane or a cylinder as the adjustable volume, whose size would be adjusted using the hydraulic pump. The ballast system for this AUV could have one or more membrane-type tanks, why it was studied if it is possible to place two small hydraulic accumulator bladders or similar membranes in fore and aft of the hull in order to use them not only for buoyance control but also pitch. Combining pitch trim and buoyancy control sounds very good regarding the space limitations, however a brief calculation shows that within the limitations of dimensions and volume of the ballast tanks it is difficult to obtain significant amount of pitch. The submarine should be stable, meaning that the center of mass should be lower than center of volume, and if the distance between these two is the least bit long, the pitch will require too much torque to be achieved with ballast system. Using two separate adjustable volumes would require more piping, at least two valves and would require a more complex control system. Thus the best solution seems to be a simple pump-controlled system that uses one or perhaps two membrane-type adjustable volumes with valves to open or close the flow path between pump and the adjustable volume. Regardless of the probable complexity and inefficiency of the pitching effect, the maximum pitching torque achievable with reasonable sized ballast bellows in fore and aft of the submarine was estimated in **Error! Reference source not found.** on the next page.

The possibility of two separate tanks is something to take into count considering options where to place the ballast tanks and what shape and type they would be. Placing one or especially two bladders outside the hull seemed like a bad idea, because it would make the total dimensions of the robot way bigger than the requested 60cm diameter and prevent achieving the spherical shape which is considered as a requirement. Thinking of a space-efficient solution a flexible hose in metal tubing was considered, outer diameter of 40mm hose two full revolutions around the hull would produce enough adjustable volume for this application and it would not increase the dimensions of the hull remarkably or compromise the spherical shape too much. That is a good option, should the ballast tank be placed outside of the hull. If not, then probably a good construction is a cylindrical shaped space inside the hull, where a membrane-type adjustable volume can be placed. In the case of two separate tanks it would naturally require two of these cylindrical shaped housings for bladders. This kind of ring around the robot would probably be very difficult structure considering the positioning of scientific instrumentation and servicing of the robot between missions. Also dependability might be an issue, and this kind of structure is a bit

Choosing suitable components for the system should be simple; the volume that should be adjustable needs to be close to 3 liters or bigger and a 5-liter hydraulic accumulator is easily available product so a spare bladder for such is a justified part to consider further.

The robot should be able to pitch 90 degrees both up- and downwards, and it was obvious that if it is possible to create the torque needed for pitch with the ballast system it should be done; if not, a separate pendulum system is needed to achieve pitch. Maximum achievable torque with two separate ballast volumes was estimated using 25cm as the approximate distance to the center of hull. The torque will be limited, because pumping oil from a bladder to other moves the weight but it also moves the center of buoyancy, and only the remainder of these two is the difference in buoyancy force and gravitational force. This is to say, that when oil is moved from an adjustable volume to other the same volume will be replaced by water. In case the system should leak, the preferred oil choice is transformer oil which does not cause any problems with electronic components in case there is oil spilled on electric components. For example, Teboil Transformer oil has density of 0.88kg/l, which will be used in the estimation of achievable pitching torque. (10) The principal idea is to calculate the torque achieved by moving oil from one bladder to another assuming the volume of both of the bladders is the maximum needed total adjustable volume, i.e. the needed buoyancy can be achieved with either of them alone. This calculation does not apply when moving oil from the tank to a bladder, only when moving the oil from bladder to another as moving oil from the tank to bladder would also cause change in the buoyancy force instead of just pitching force.

$$\Delta F_{pitch} = \Delta V_{adjustable} * (\rho_{water} - \rho_{oil}) * g \ , \tag{4.1}$$

$$\Delta \tau = \Delta F_{pitch} * x_{volume} \ , \tag{4.2}$$

$$\Delta CgCv_{max} = \frac{\Delta \tau}{m_{robot} * g} \ , \tag{4.3}$$

The result of above is a total pitching force of 3.5N, which is quite little compared to the over 100kg mass of the robot. In addition, the distance between the center of robot and the adjustable volume is not very long. These two combined result in a maximum achievable pitching torque of 0.88Nm. By placing this value in the equation (4.3) above, result states the maximum distance between center of gravity and center of volume, which still would allow pitching of the robot with the specified torque. In this case this distance is a bit less than 1mm, but this is just the effect of one bladder so it must be multiplied by two to have the total effect. With the effect of two bladders, this distance would be approximately 1.8mm, which still is marginal. In other words, pitching the robot using ballast bladders as trim weight is not realistic because of the very low achievable torque. As a rough estimate a value of 10mm would be suitable to achieve fair stability in horizontal motion and still be able to pitch the robot. With less than 2mm distance between centers of gravity and volume the robot will be difficult to control as the stability is no more than nominal, and it will be extremely challenging to position all the components inside the robot in a way that fulfills the CoG requirement this precisely. In case of any current that causes rotational force to the robot this low torque pitch system will not be able to stabilize the robot and maintain vertical heading, which would lead to problems with the control system. Thus, the buoyancy control system will be a bit simpler than previously expected, as it seems obvious it shall only have adjustable volume in one place of the hull, not in fore and aft. If it was necessary, a separate pair of trim tanks could be added to create the torque required for pitching, but it

Another thing to consider is the center of volume or center of buoyancy, which are essentially the same. That is to say, when the bladder is filled with oil, it increases the total volume of the robot, but also moves the center of buoyancy, which may have to be compensated somehow. This would create extra complexity for control system, and hence the movement of the center of buoyancy in relation to center of mass should be kept as small as possible. In case of the bladder being placed in the bottom of the hull and the oil reservoir in circular shape around the volume the weight distribution doesn't change much, but the center of buoyancy does as the addition or decrement in buoyant volume is at one place close to the surface of the hull. Total controllable volume is designed to be three liters, if it were placed averagely about 5cm from the surface of the hull at the bottom of the submarine it would create a significant torque when the submarine is pitched. Below are the calculations on change of the center of buoyancy assuming that the oil is placed in a ring-shaped tank around the adjustable volume, i.e. the center of gravity does not change during filling or draining of the volume.

$$\Delta F_{buoyant} = \Delta V_{adjustable} * (\rho_{water}) * g \ , \tag{4.4}$$

$$\Delta \tau = \Delta F_{buoyant} * x_{volume} \ , \tag{4.5}$$

The result of placing values to the equations (4.4) and (4.5) shows, that using a structure described above causes a lifting force of 29 Newtons to distance of approximately 25cm of the center of the robot. That creates significant amount of torque when the robot is not facing directly forward. The CoG is actually moved by approximately 18mm. This change in CoG creates a torque of 7.35Nm when the robot is facing completely up or downwards, and most probably it will not be possible to be compensated by the pendulum mechanism. As the previous values show, it is not suitable to use a system which has the oil reservoir placed around the bladder structure as it would create significant torque when the buoyancy is altered. This torque effect should be avoided by moving the oil reservoir away from the bladder structure so that the mass center moves approximately as much as does the center of volume. Keeping this distance constant while altering the volume of the robot all but requires the oil reservoir to be placed close to the center of gravity, then while increasing the volume of the robot increases the buoyant force at the same location the weight is transferred to. Oil is not just as dense as water (10) (8), but the difference is probably small enough to be compensated with the pendulum which is anyhow required for pitching the robot. This effect is actually calculated earlier, and the results shown in equation (4.1) are applicable in this case, assuming that the oil reservoir would be placed exactly at the center of volume. The 1mm transition should not have significant effect on the control dynamics. Repositioning of the oil tank causes need to reposition some equipment inside the hull, but it seems mandatory to discard the idea of having the oil tank and bladder structure placed together.

Another considered issue about the ballast system has been the location of the adjustable volume in relation to the center of volume and center of gravity. After having thought about ways to place oil reservoir so that changing the amount of oil in reservoir would compensate the torque created by the adjustable volume, it was realized that if a fluid of same density as water was used, the location of the adjustable volume would not matter as long as the oil reservoir is in the middle of the volume of the robot. This kind of oil seems to be available as shock absorber oil, and the viscosity can be selected to be suitable for the hydraulic pump. Silicone based shock oils have density of 0.95-0.98, which means it has less than 5% difference in mass compared to water. If the adjustable volume is placed 20cm off the center of volume, three liters would create a weight change of 0.15kg, which would result in a torque of 0.3Nm. That is very minimal and it can be very easily compensated with the pendulum mechanism in the robot, which has maximum torque capacity of about 7Nm. There shouldn’t be a reason why silicone oil would not work in the hydraulic system, and thus it is the choice for this application.

Finding a bladder suitable for this application eventually prove out to be practically impossible, because the dead volume in bladder-type structure is always bigger than in piston type versions. Also the shape of the space available is quite thin, but length and width can be extended a bit. As a conclusion, only structure that can be fit to the tight space in the submarine is to use more than one piston barrels as the adjustable volume. To keep the structure as simple as possible, a two-barrel structure was designed to be tested in the robot. The structure consists of two pistons, two barrel pipes and two endcaps, and it has got an effective volume of 3L, with minimal dead volume as the pistons have reliefs in the middle to allow the installation of a hose connector. This allows the piston to move all the way up to the barrel endcap, leaving dead volume to only the length of the piston. A demonstrational picture of the parts below:

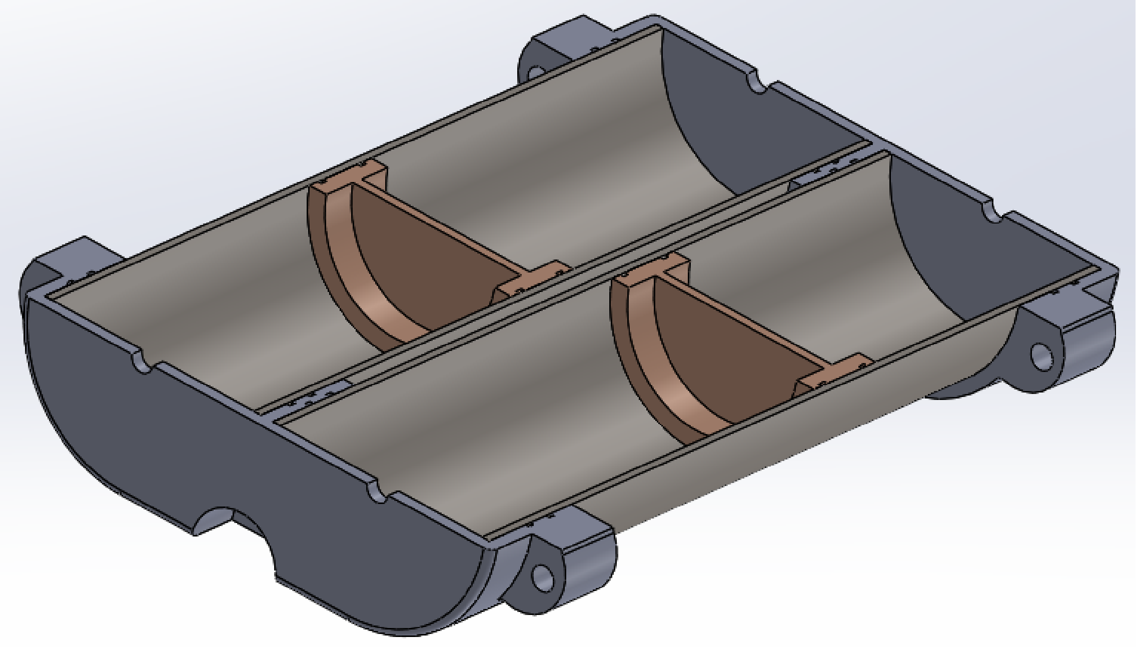

Figure 7: Section view of ballast barrels

Some details needed more attention, as in this structure there will be water on the other side of the piston and oil on the other side, this causes many requirements for the materials used. For example, the parts have to withstand oil and resist corrosion, and the seals and guiding rings for the pistons have to work with water lubrication as well as oil lubrication. Besides these requirements they should also be low friction and physically small in order to keep the piston as small as possible. The minimum length of the piston is determined by the maximum allowed tipping of the piston, and in this case the clearance might not be the only restricting factor; the width of gliding rings might also be rather much for this application, which for example in a Trelleborg glydring is 12.8mm. The drawn model has only 30mm wide pistons, so obviously this wide wear rings are not suitable as such. (11) A company called Top-Osa is able to deliver wear rings with custom dimensions and they have a broad variety of sealing product profiles to choose from (12). This gives the opportunity to maintain the 30mm thick piston and have the dead volume on the barrels minimized, while leaving possibility to choose a sealing profile to suit the relatively low pressure level compared to hydraulic systems. The length of the piston can thus be determined by the amount of allowed tipping angle, and if for example one degree of tipping angle is allowed, the clearance in total is half a millimeter, so 0.25mm clearance on each end will allow for one degree tipping of the piston. This can be seen as the limiting factor for the piston length, because tipping of the piston might cause sticking of the piston, which would jeopardize the reliability and thus is unacceptable.

4.2 Oil reservoir

The properties of the pump for ballast system specified the used fluid as oil of some sort, and the use of oil requires storing it inside the submarine. It makes the design quite simple and space-efficient if the in-hull oil reservoir is placed around the bladder structure, thus creating a flat floor inside the hull. This kind of fixed oil reservoir needs some arrangements to ensure oil supply for the ballast pump in any true coming position, but it saves usable space inside the hull, and saving space is of very high priority in this application.

One issue that was mentioned earlier is the possible oil leakage onto some electrical components inside the hull. Considering the fact that the submarine should be able to be pitched 90 degrees in both directions, the oil reservoir breather is an obvious source for oil leaks of some amount. That gives the idea of using a pressurized tank, and after brief speculation, it seems like quite a good idea. With pressurized tank it would take a bit power to drain the bladder and force the oil into the reservoir, but that power is not significantly high and much of it can be utilized when the bladder is filled. This reduces the power consumption when filling the bladder at maximum designed depth, as there will be some pressure in the tank, causing the pressure difference over the ballast pump to be not as great as it would if the tank was not pressurized. This kind of construction would also decrease the pressure fluctuation inside the hull, even though the components inside the hull should not be affected by moderate pressure fluctuations. Reduced need for power to increase buoyancy at great depths and decreasing the risk of oil leakage are however the major advantages of the pressurized tank construction. There are however some disadvantages in using the pressurized tank; the pump seals must be capable of handling the pressure in the tank, which means replacing shaft seals and adding a support for the seals. The initial pressure in the tank and maximum pressure in tank must also be monitored and set carefully to maintain enough pressure in the tank in every situation to ensure good oil feed for the pump but still keeping it low enough for the pump seals.

Considering the fact that the submarine shall be pitched 90 degrees in both directions, the oil pickup tube in the oil tank will need to be of unusual type in order to ensure oil feed for the pump in all expected positions. Using a pressure accumulator as a tank would be an option if it wouldn’t cause issues with weight and weight distribution; it is highly unlikely that a hydraulic accumulator maintains the same center of mass lengthwise. Horizontally placed cylindrical tank should maintain the same center of gravity regardless of the level of oil inside it, but in this kind of structure splash preventing plates might be necessary to prevent the oil movement swaying the submarine.

The oil tank for ballast system is intended to be made pressurized, which limits its shape and requires more structural rigidity. Attention must also be paid to shape of the tank, as the oil movement should not affect the stability of the robot, or slight unintentional tilting of the robot should not cause significant change to the center of the mass. That means the bottom of the tank must be shaped so that the midpoint of the bottom is where the oil is collected even if the submarine is a bit tilted. Optionally ensuring oil availability for the pump at all conditions, a special oil pickup can be made. Controlling the roll is done by using the vertical thrusters when necessary, but the robot should anyhow be structurally stable in order to avoid frequent thruster usage to maintain horizontal heading. This kind of tank is not available to be bought, so the requirements must be compromised or the tank must be designed and manufactured purposely for this application.

Because the pitching of the robot was estimated not possible using only two adjustable volumes, the torque needed for pitching needs to me acquired somehow. It will be made using a separate pendulum mechanism, which relates to the buoyancy system because the pendulum should be pivoted in the middle of the robot, and on the other hand, the center of gravity of the oil reservoir should be in the middle of the robot. That is why it is intended, that the pendulum should be attached to the reservoir, and move around it. This creates the need for a cylindrical shape for the reservoir. The sides of the robot also need a support to prevent the detachable side panels from being pushed in, which means the oil reservoir should either act as a structural support itself or at least enable installation of such.

One of the main requirements of the robot is reliability, and usually simple is reliable; the structure of the oil reservoir for ballast system should be easy to manufacture and difficult to break. It should also be possible to disassemble the reservoir if for example an oil change is needed. These things were considered when a simple to manufacture drawing for oil reservoir was made, and it also had a supporting rod going through the reservoir. The idea is that the smaller diameter ends of the reservoir act as attachment surfaces for the pendulum mechanism and the reservoir itself, and the rod inside it acts as the support structure for the hull ends of the submarine. Earlier it was noted, that oil pickup tube will need to be extraordinary as the reservoir will be pitched with the robot, and oil supply for the pump has to be guaranteed in all possible positions of the tank. The 3-D sketch of the reservoir is shown below in Figure 8: Oil reservoir 3-D sketch, where supporting rod is colored blue and the oil pickup light green. The oil pickup has a weight in the end of the pickup pipe to keep it pointing downwards, and there will be a flexible hose to a penetrator, whose place will be confirmed later on.

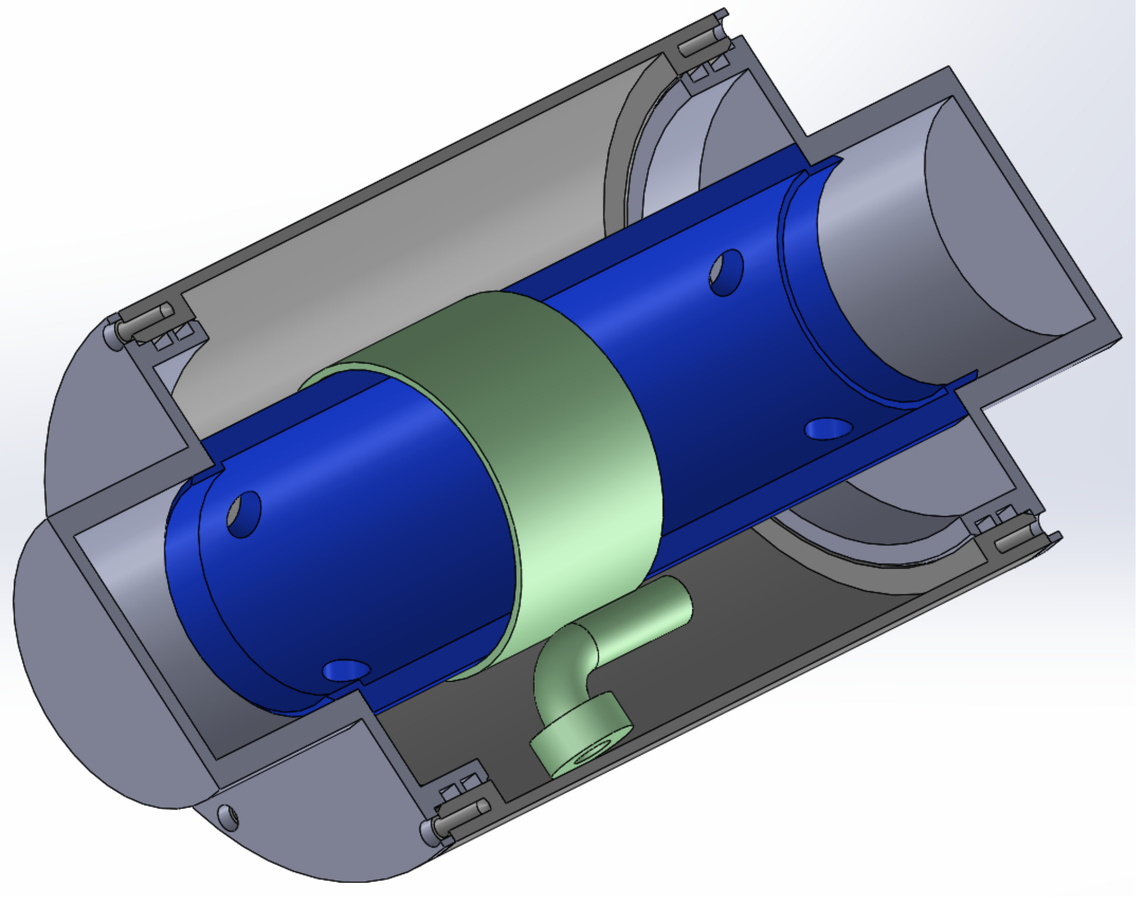

Figure 8: Oil reservoir 3-D sketch

4.3 Pump and motor combinations

The main components for this ballast control system are the hydraulic pump, motor for the pump and possibly required reduction gear between them, and the bladder. Speed of this system is not as high a priority as size, so a quite small pump should be used. There are also miniature hydraulic pumps manufactured by i.e. Hydroleduc and Takako Industries, but their reluctance to provide quotes and more specific details arouse interest in easily available products that would be small enough to be suitable for this submarine. This soon led to intention to use a Bosch Rexroth pump, AZPB-32-1.0 to be more specific. This pump has a displacement of $1\,\frac{\text{cm}^3}{\text{rev}}$. The selection criteria were availability, small size and a maximum flow that allows to fill or drain the bladder in reasonable time. The smallest off the shelf pump Bosch Rexroth offers is this one, which is spec'd to a maximum flow of six liters per minute, which means that the designed ±1 liter can be achieved in ten seconds when running the pump at full speed. That is actually more than adequate value to start with as the ballast system doesn’t need to be particularly fast. The physical size of such pump is about 8cm in all length, width and height. (13)

Manufacturer provides charts of the required power and torque in different conditions, and because this robot is designed to be able to dive up to five hundred meters depth the initial requirement is fifty bar of pressure. However, some safety margin should be left, and it was agreed that designing the system for 70 bar is suitable margin. At 70 bar the pump requires less than 1.5Nm of torque according to the manufacturer documents, and at maximum speed the power consumption would be approximately 900W. That is loads of power, but as long as the torque term is fulfilled and minimum speed of 750 rpm is exceeded, the speed can be reduced in order to reduce the maximum used power when necessary.

Another task is selecting the motor, which then determines if a reduction gear is needed or not. Very small sized electric motors tend to make low torque relative to power, thus probably a reduction gear will be necessary. First select criteria is the voltage of the battery pack, which at this point of design process is not yet confirmed. The main control system and the thrusters will run on either 12 or 24 volts, but most probably there will be also some 24 volt devices. At this point it would be a safe bet to choose a motor running on 12 volts with suitable power characteristics, but it seems that motors with power rating even close to the need are running on more than 20 volts. It makes sense regarding the needed current to achieve about a kilowatt of power with only 12 volts, but in this application low voltage might be required by the scientific instrumentation. It would allow the use of a single common voltage throughout the whole electrical system and that would increase the efficiency and save space. If a higher voltage is required for only some components, it must be produced either by adding a separate higher voltage battery pack or by adding an inverter or converter to generate the desired voltage from the battery pack voltage. This kind of inverter is hard to find in power range required by the ballast system, and it takes much space. Quick search and questioning came up with one seemingly useable solution, it provides 950W continuous power at various output voltages, but it is physically too big to fit in, as it is 240mm long, 145mm wide and 25mm thick. (14) Despite the significant size of the converter it is just about powerful enough to power the motor for the ballast system pump. It is preferred not to use converter but find perhaps two motors that run on 12 volts and use them in tandem to power the pump, or then the main electrical supply should use 24V.

The Rexroth hydraulic pump has maximum rotational speed of 6000rpm, and it is recommended to be connected to power source through a clutch that excludes radial forces to pump input shaft. Thus it wouldn’t need much more space if a reduction gear would be placed next to the pump, and the reduction gear would allow the use of brushless electric motors used in RC-cars, boats or helicopters. They use very compact motors, which have stated power and voltages ratings of more than 600W at 12 volts, but these motors are not meant for industrial use and most end-users do not have means to measure the actual output of the motor, which arouses the question of authenticity of the power ratings. That is why it seemed reasonable to measure the actual output power of a RC-car electric motor and speed controller combo that was specified quite close to the requirements of this application.

Having considered these options, it was obvious that using as much power and as low voltages as suggested above would not be the ideal solution, and if it was possible to find even smaller a pump it would be beneficial considering not only the power issues but also the space limitations. Therefore, a Jung-Fluid small hydraulic pump was ordered even though the fact that it was being marketed to be used in RC-excavators arouse some suspicion about the dependability and quality of the pump. The chosen model, IPZ1-HR-10, has a physical size of about 4cm in each direction, which really is small for a hydraulic pump advertised as capable of 120bar pressure and requires at maximum 720W input power. Maximum flow for the pump is a bit less than 2l/min, which is adequate for the purpose: time required to change the buoyancy by 1 kg takes about half a minute at full speed. As the system also needs a valve to be able to close the flowpath between adjustable volume and the pump, a servo-operated directional valve was ordered with the pump in order to be able to test the complete hydraulics of the ballast system. The directional valve was significantly smaller than an on/off valve offered, so it was chosen to be used instead of the on/off-one. This would also give the option of always using the pump in the same direction, as the manufacturer states a fixed direction of rotation for the pump. (15)

To have some idea of the properties and quality of the pump, it was disassembled to observe the structure and find out a reason for the one-way operation only. It became obvious that the pump seems to be of better quality than one could have expected from a “toy”. The machined surfaces seem good and the is no slack that can be felt by hand or measured with a digital caliper. Pictures of disassembled pump can be found below.

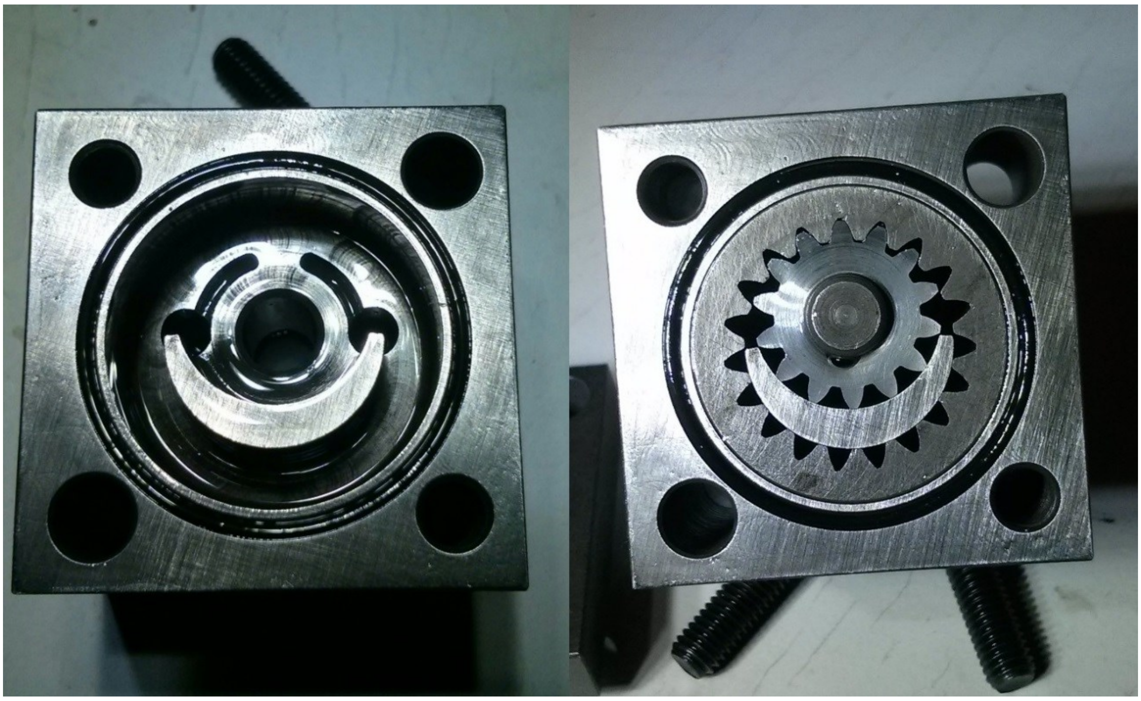

Figure 9: Disassembled pump

The pump is a very simple inner gear type pump, and all the parts are completely symmetrical except for one drilled flowpath from the shaft seal casing to the suction side of the pump. The company sells both clockwise and counter-clockwise rotating versions, which most probably are the very same pump except the drilled hole mentioned. Advertised mechanical efficiency for the pump is 0.5, which is not very good for even a gear pump, but the requirement of very small space compromises some other properties. Picture of pump internal parts and the only asymmetric bit, an extra flowpath in the inlet port of the pump below.

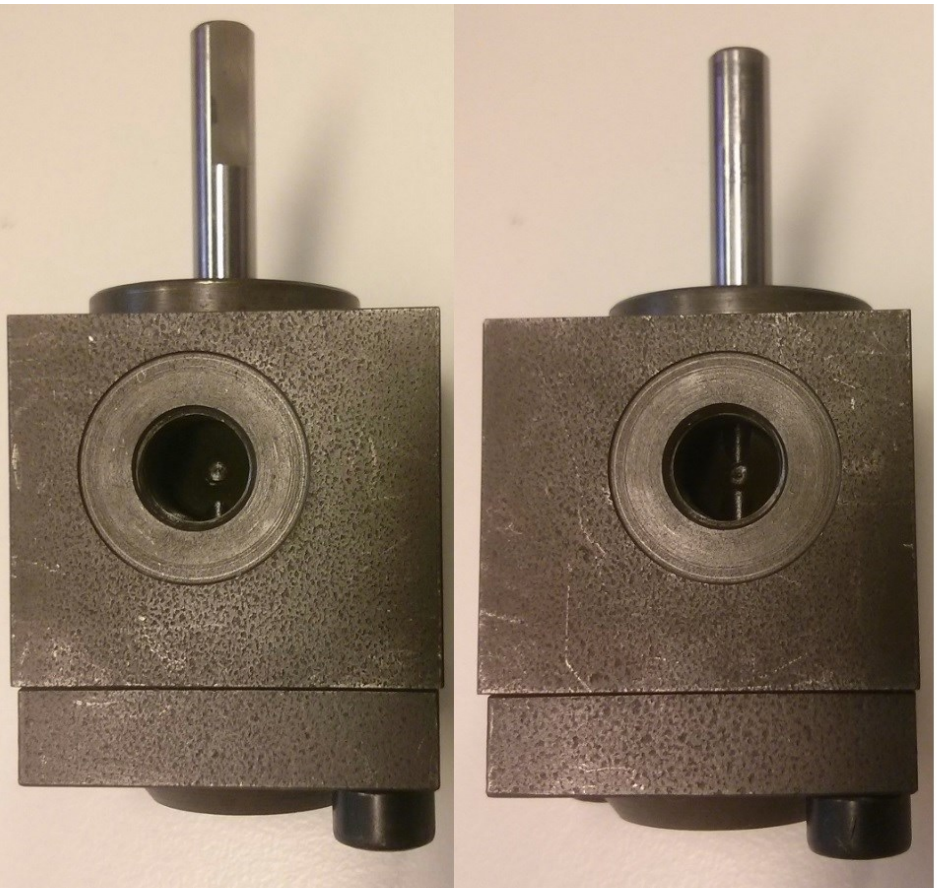

Figure 10: Pump outlet and inlet ports

This pump also requires less power than the previously mentioned Rexroth pump, which allows the use of smaller motor. The maximum power this pump needs at 60bar pressure is 360W, which can be easily achieved with an RC-car brushless motor. It needs a reduction gear, because the RC-motors are generally designed to be run at something between twenty and fifty thousand rpm. A quite slow motor with a reduction gear is still a compact setup and is easily available so this is the design for the first robot to be built. The motor is Turnigy Trackstar 3520kV, which is spec'd to 660W maximum power and a nominal speed of 38000rpm (16). A few different gears were ordered so it is possible to test the actual performance of the system with different gear ratios and to see how changing the ratio affects the startup of the motor and on the other hand how fast would the motor actually be able to rotate under full pressure at the pump. The maximum speed of the motor can be limited by the control system, so it is not dangerous if the maximum rpm of the motor would result in excess speed for the pump. Considering the startup torque the gear ratio should match these maximum revolutionary speeds as close as possible. On the other hand, manufacturer allows the pump to be run at higher speeds when under light pressure, that means possibility to speed up the change of buoyancy when the robot is in relatively shallow depth.

4.4 Directional, pressure relief and shutoff valves

The buoyancy control system is primarily used to maintain neutral buoyancy, which is affected by the compression of the hull and density of the water, which changes as a function of temperature. It seems that it is difficult to find a micro-hydraulic pump that is reversible, but having disassembled the Jung-Fluid gear pump chosen for this application it seems that only reason for this limitation is the shaft seal housing being drained into the suction side of the pump. This means that the pressure on the suction side, which is the same as on the shaft seal, should be kept low, but it does not say the oil flow direction could not be also to the tank. This simplifies the system quite a lot, as a directional valve for swapping the pump inlet and outlet ports is not necessary and the space can be used otherwise. This conclusion is followed by a decision to use a very small directional valve as an on-off-valve, because an actual one would be rather large and the selection seems very limited. The directional valve is designed to be used in RC-excavators and similar machines, the maximum working pressure is 70 bar and the flow rate is actually not advertised. (17) The valve is designed to be operated by a RC-servo, and the physical size of the valve is almost ridiculously small; without the servo and its mounting parts the valve itself is 20mm wide, 20mm long and about 28mm high.

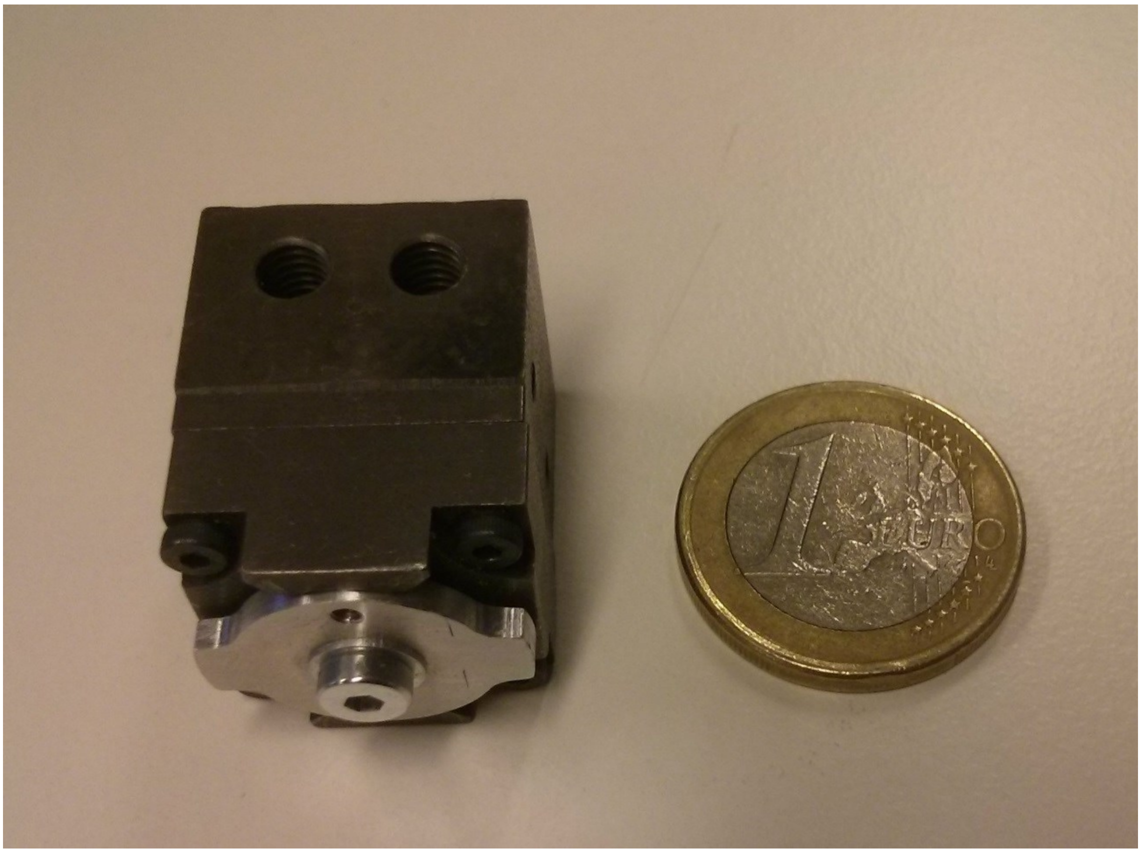

Figure 11: Size of the valve, coin for comparison

The valve is actually smaller than the mini-sized servo that the manufacturer recommends to operate the valve; the servo increases the dimensions to 20mm width, 38mm length and 62mm height. This is still smaller than coil-operated valves, and it only consumes energy when the position of the valve is switched. Coil-operated valves are either normally closed or normally open, and keeping the valve in the alternative position requires constant power to the coil. As the hydraulic unit changes the buoyancy quite slowly, power used by the coil should be taken into account in estimations of power consumption if a coil-operated valve is used. A picture of valve with attached servo below.

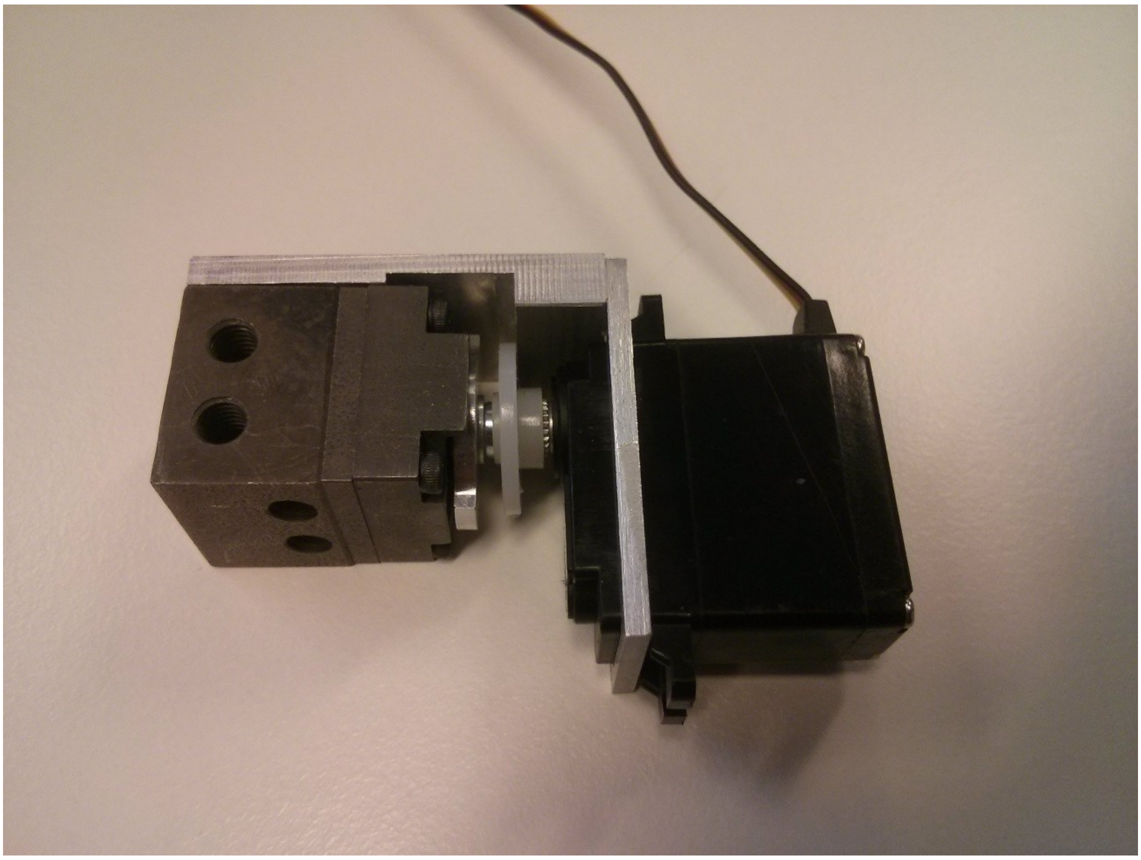

Figure 12: Valve and servo assembled

The image above also shows the hydraulic connections of the valve, they are 5mm thread holes intended to seat hose connectors. They have a very limited surface area for flow, which causes worry about the pressure loss over the valve. To know more about the flow restrictions inside the valve it was disassembled, and it prove out to be of a very simple design. The machining quality seemed OK, and the valve openings seemed symmetric. The valve is specified to work at maximum of 70 bar pressure, which is well adequate for this robot. The flow rate not being advertised suggests that the flow rate for this valve is rather small, but because it will be used as an on/off valve instead of directional valve it is possible to combine the input and return ports and the actuator ports together. This will double the flow capability of the valve and our application will have at maximum about 1.8L/min flow, so the requirements are not very high. The downside when using this valve is that it is not perfectly closed even in middle position, as there are no seals between the rotating disc and the valve body it will leak a little bit through the tolerances between the disc and the body. Image of the disassembled valve and the rotating disc below.

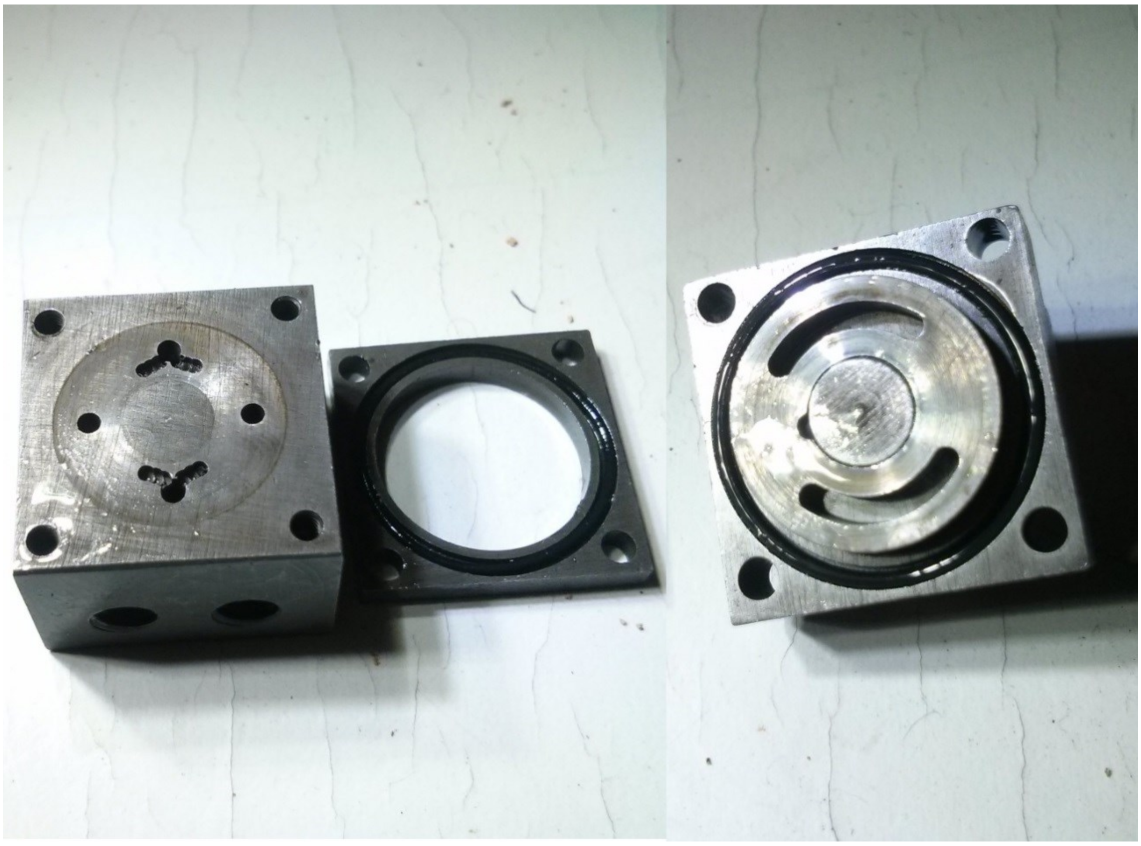

Figure 13: Valve dissassembled

The discussed valve is specified to work at 70bar, and the pump described previously is capable of 120bar pressure. The pressure between pump and adjustable volume should remain at approximately the same as the external pressure of the robot, which should not exceed 50bar. However, it is possible that the ballast cylinders will be bottomed out in some situations. Should such a situation occur, the pressure might rise very high before the motor stops due to lack of power, and the pressure might be enough to break something in such a situation. Therefore, a pressure relief valve should be used, although it seems that in this application it is necessary to produce a very simple version ourself; off the shelf, commercial products are not very small or easily available. It is anyhow necessary to build a connector that connects to two ports of the valve and has one bigger connector for pump or adjustable volume, the pump side connector could also have an integrated pressure relief valve.

5 EVALUATING BALLAST CONTROL PERFORMANCE

The main purpose for ballast system is to produce vertical force without constant use of energy. That means traveling long vertical distances is more power-efficient, but obviously “long distances” is not a very definite phrase. In order to keep the power consumption of the robot at minimum it would be very beneficial to know the distance that is more economical to travel using buoyancy control rather than thrusters. Other important thing to know is the dynamics of the robot considering the use of buoyancy control; how fast can we achieve maximum or minimum buoyancy, and how fast will the robot accelerate and travel with different buoyancy levels. The effect on robot dynamics is the most important aspect of the simulation, that gives the knowledge of usefulness of buoyancy control system in different situations. These things can be estimated by creating a system model of it and artificially testing the system in different conditions.

In order to create a bigger picture of the behavior of the robot with different buoyancy values it is possible to make some simplifications to the model without the accuracy of wanted data being reduced significantly. For example, the inertia of the moving parts is a rough estimate based on the weight and radius of the parts, and the efficiencies of the hydraulic pump are taken from the datasheet that manufacturer has provided. These estimates do not affect the behavior of the dynamic model of the robot, but rather might cause some error to the computational power consumption of the system or create negligible inaccuracy in the time required to change buoyancy.

5.1 Ballast system model

Modeling the ballast barrels requires also modeling of the systems that actuate the ballast pistons. These actuating models consist of hydraulic pump, reduction gear and electric motor. Besides the actuating parts it is also necessary to evaluate the effect of adjusting the buoyancy on motion dynamics of the robot. A picture of how the different subsystems relate to each other in the model below. The picture shows the principal behavior of the model, where an input is given to the motor controller, which is actually a P-controller, that compares the actual rpm and the desired rpm and generates a value that is fed to the motor. The motor gives out a revolutionary speed and powern soncumption as a result of control input, load torque and current speed.

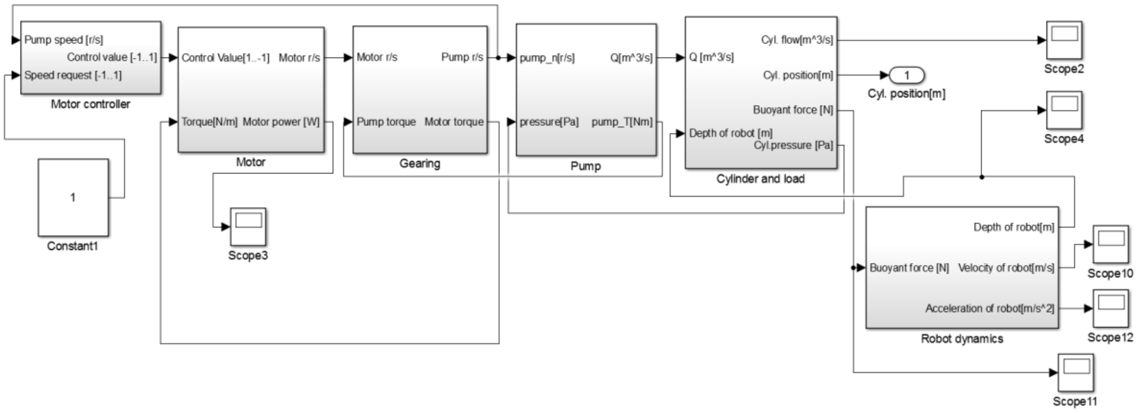

Figure 14: Overlay of ballast system block diagram

The most interesting result of the simulation is the dynamic response compared to the use of ballast system, and the robot dynamics part of the model is actually quite simple. Buoyant force and drag force cause accelerating and decelerating forces, which are easily turned into acceleration of robot by summing these forces and dividing by mass, after which the acceleration can be integrated to velocity and location. The velocity also affects the drag force, creating a closed loop in the subsystem. Principally this block represents a basic physical equation, namely Newtons second law, and also the relation between acceleration and distance (18).

$$F_{net} = m * a \tag{5.1}$$

$$\mathrm{r} = \frac{1}{2}at^2 + \mathrm{v}_0 t + \mathrm{r}_0 \tag{5.2}$$

The overlay of the model is shown in Figure 16: Cylinder model subsystem below.

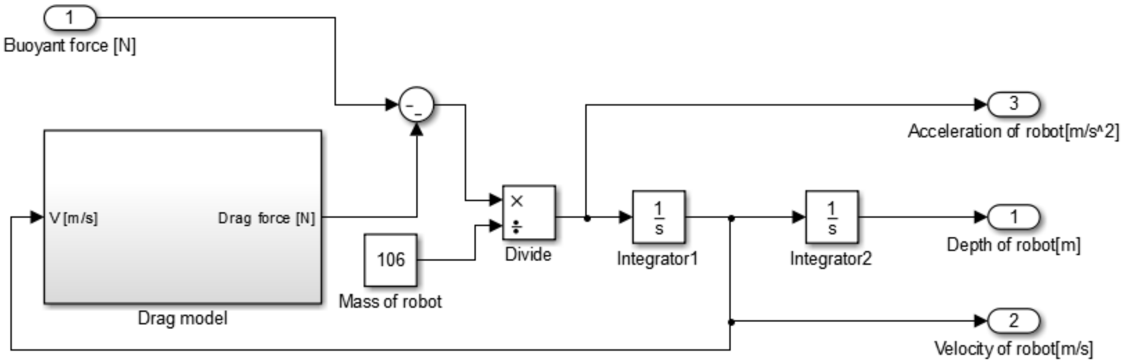

Figure 15: Robot dynamics model

The most complicated part of the model is the cylinder model, shown in Figure 16: Cylinder model subsystem, which has a volume model included. The volume model takes into account the compressibility of fluid and the parts that contain fluid. It receives fluid flow from the pump model and external pressure from the control model, and as outputs there are cylinder position and buoyant force. The cylinder velocity is also taken into account in the friction model, which adds movement resisting counterforce in stationary and moving situations. This force affects the output pressure of the block and thus affects the required pressure from the hydraulic pump. The friction force equation represents the equation presented in Hydraulic Cylinders in equation 21. (19) The volume model is a mathworks volume model available for MatLab. (20), and hydro-mechanical efficiency is a generally used estimate. The initial equations for volume model are presented below.

$$V_f = V_c + \frac{V\_c}{E} p \tag{5.3}$$

$$q = \frac{V\_c}{E} * \frac{dp}{dt} \tag{5.4}$$

This part of the model also contains monitoring of the position of the cylinder, and blocks that prevent the cylinder position from going further than the cylinder length actually is. These blocks do not do anything unless the cylinder position reaches the end of the cylinder, in which case they create more than enough force to stop the movement at the end of cylinder. Actually they work as an extremely strong spring, they only create force when the cylinder position reaches the maximum or minimum, and forces it to stop. Sizes of volumes and mechanical efficiency are estimates. Below an overlay picture of the subsystem.

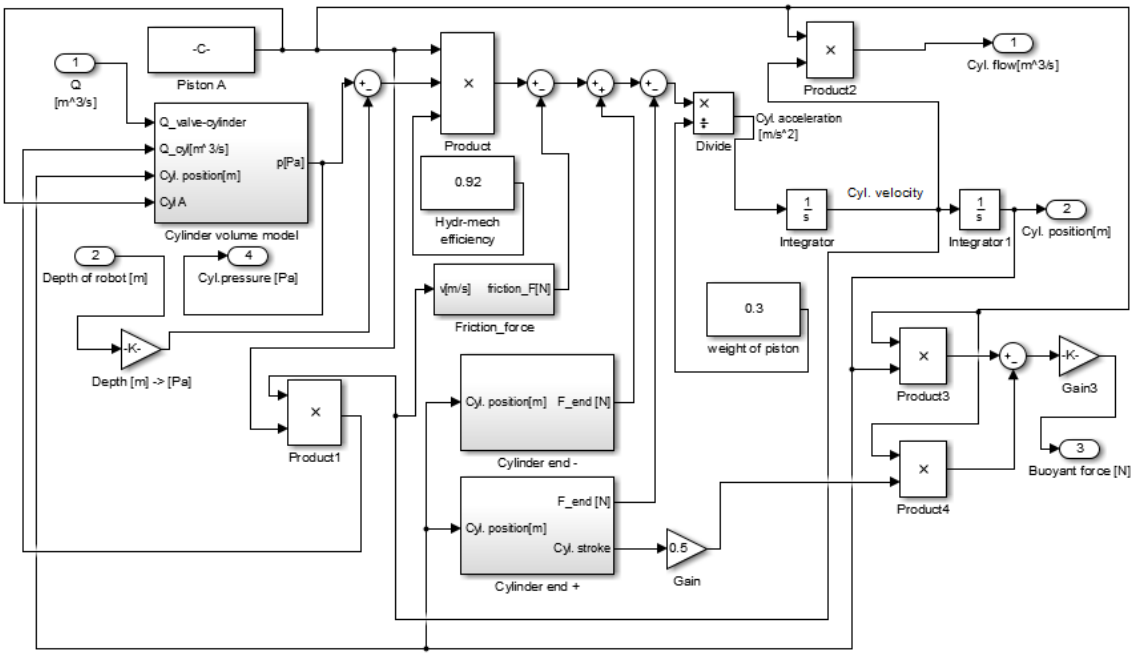

Figure 16: Cylinder model subsystem

The subsystem that actually actuates the cylinder model is pump model. In this case, it has been simplified a bit, the pump manufacturer provides a diagram of the produced flow at different counter-pressures and this is used to evaluate the pump flow in the model. The torque needed to operate the pump is calculated using the revolutionary volume of the pump, pressure and mechanical efficiency. Mechanical efficiency was evaluated by comparing power consumption chart provided by pump manufacturer to the hydraulic power in the pump output, which also is provided by the manufacturer. (15) The equation for the torque output is shown below, and the output flow is read from a chart as a function of revolutionary speed and pressure. Layout of the model can be seen in Figure 17: Pump model.

$$\tau = p * V_{rad} \tag{5.5}$$

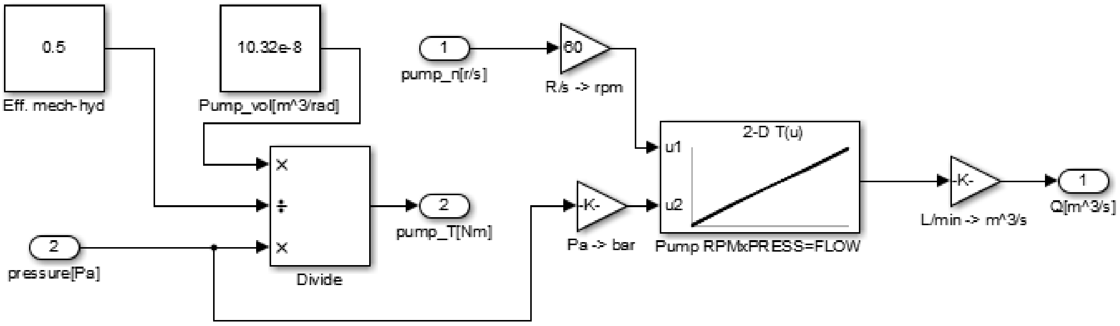

Figure 17: Pump model

The model for the electric motor is also simplified version that uses a theoretical torque curve multiplied by control value to create the actual torque output for the pump. The torque of the electrical motor is evaluated as classic torque curve, which starts at maximum torque at standstill and then linearly goes down until it reaches zero at the maximum motor speed. There is also a combined estimated inertia factor to take into account the mass of gears and other rotating parts directly related to the motor. The subsystem outputs are revolutionary speed to the motor and motor axle power for user evaluation. Picture of the subsystem below.

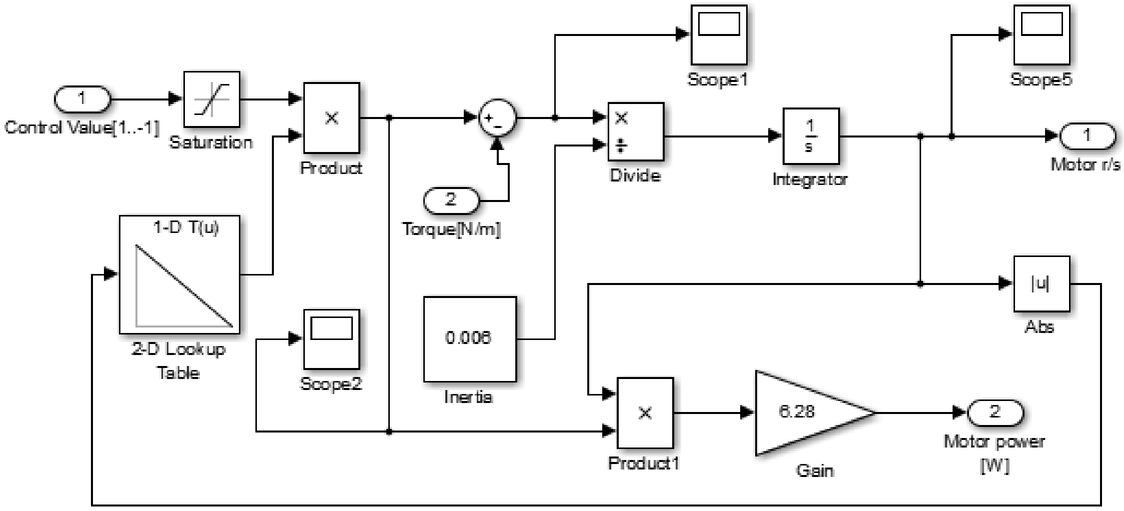

Figure 18: Motor model

There are also models for motor speed control and gears between motor and pump, but they only contain multipliers for rpm and torque with a coefficient for efficiency, and the speed controller is ultimately simple P-controller. In the actual robot, the P-controller will be replaced, and for this test of robot dynamics and volume control performance, this kind of simple control is suitable.

5.2 Simulation and evaluation of results

The results for ballast actuated vertical movements were calculated assuming that maximum achievable negative or positive buoyant force is used, because the thrusters have significantly more force it is reasonable to try to keep the motion speed close to the same in both cases. Acceleration is significantly slower when using ballast system, because the thrusters can produce the maximum force practically instantly, whereas it takes almost a minute to change buoyancy from neutral to full positive or negative. This slow acceleration can be clearly seen in the velocity graph below. The buoyancy is changed at the maximum speed and the maximum buoyancy is reached in about 57 seconds, and the maximum speed briefly after that. The thrusters reach the desired force almost instantly, and the acceleration using constant force takes a bit less than ten seconds, which really points out the fact that ballast system should not be used for short distances.

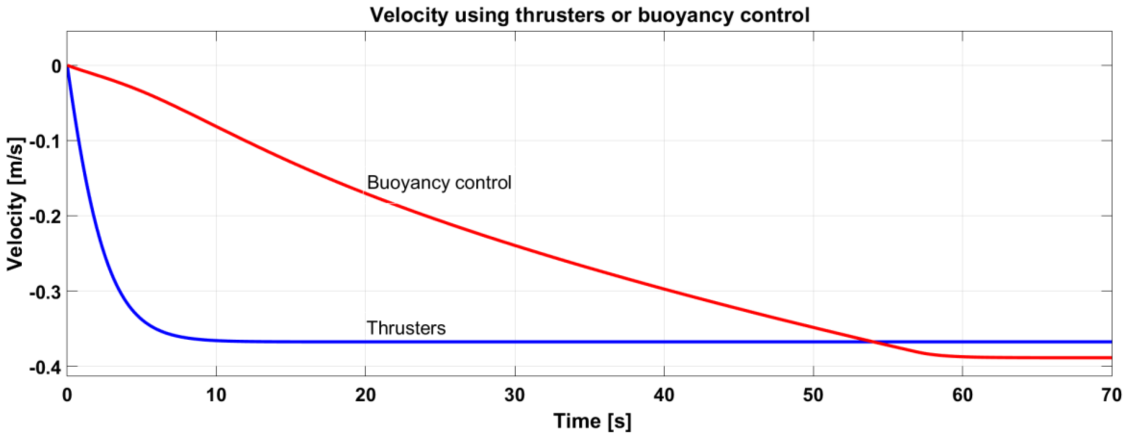

Chart 5: Velocities using thrusters or ballast system

The power consumption is the most important aspect to consider, as power supply is limited on an autonomous robot. The power consumption differs significantly between use of thrusters and use of ballast system, as the distance traveled does not affect the power consumption of the ballast system, but the thruster power consumption is directly related to the distance. The power consumption of the ballast system, on the other hand, is related to the depth of the robot at the time of increasing robot volume. By collecting different estimates for power consumption using thrusters and combining the ballast system power usage, the result can be seen in Chart 6: Power usage of vertical movement. It gives a principle guide of when to use thrusters and when alter the buoyancy: above the red line is the area where thrusters should be used, and below it the buoyancy control system should be used. The power consumption for thruster power usage was evaluated so that the motion was stopped by drag of the submarine, without using the thrusters to slow down. The ballast system power consumption was evaluated at different depths, assuming that oil in ballast pistons is pushed back to the oil container by the external pressure of the robot, without need to use energy to pump the oil back to the container. These results are combined into a graph below to visualize the differences between different methods to move vertically.

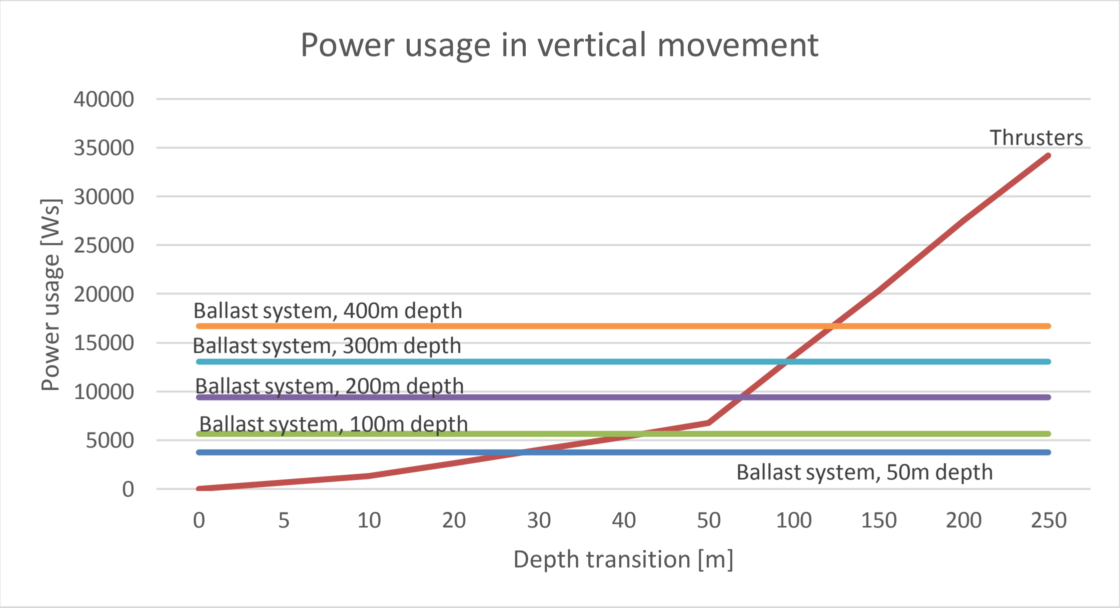

Chart 6: Power usage of vertical movement

When evaluating the accuracy of the simulated results, they should be used as guidelines rather than absolute factual numbers. There are some values for efficiencies and losses in the model that are only estimates of a generic similar component, and as there is not a physical model to actually compare the results at this moment, they cannot be held completely accurate. Evaluating by power consumption versus hydraulic power, the efficiency seems realistic and the speed of the system is limited by the maximum flow of the pump, thus the dynamics are most probably quite accurate. These were the most important things to evaluate using the model, and it the results do help understand the effective way to use ballast system or thrusters.

5.3 Discussion on simulation results

The main value for the energy consumption comparison was to evaluate, when it is beneficial to use ballast system instead of thrusters, and the results were not very adorable for the ballast system; the power consumption is quite high, and it is thus not beneficial to use buoyancy control in many cases. Ideally, the ballast system should be able to save energy in quite short distances compared to the thrusters, but the efficiency of the system is perhaps surprisingly low. The initial reason for this is 50% hydro-mechanic efficiency of the hydraulic pump, especially when it is combined to volumetric efficiency of about 85-95% depending on the pressure required. These values result as total efficiency of about 45% for the hydraulic pump alone, and when losses from gears, hydraulic pressure loss in pipes and valves and the losses in electric motor and motor controller are also taken into account the total efficiency is rather low.

It would be worth a thought to evaluate the possibility to use a pump of different principal structure; the Jung-Fluid one is an internal gear pump, whereas for example Takako Industries produces an axial piston pump with very similar pressure and flow characteristics, and while being twice as long it also has twice as good advertised efficiency. If the power consumption of the ballast system is reduced to roughly a half of what was evaluated previously, it would be a realistic vision to use ballast system also for vertical movements of about twenty meters and save some energy by doing so. The next step to improve the design will be to source another pump for tests and do the similar comparison again.

Recovering energy from the ballast cylinder movement is an interesting idea, because the fluid in the ballast barrels is under the same pressure as the whole robot. Converting the energy used to push the pressured fluid out back to electricity requires using the hydraulic pump as a hydraulic motor, and the electric motor as a generator. It might be possible by using regenerative braking allowed by the Vedder speed controller, but the significance of this will not be remarkable as the efficiency of the pump is relatively low, and when it works as a hydraulic motor, it will not be any better. Besides, the efficiency of the motor and speed controller in the regenerative state are unknown, which makes it very difficult to evaluate the amount of energy that can be recovered. Thus, this amount has been evaluated as zero in the previous simulated results.

There is however a perhaps significant advantage in using regenerative braking instead of traditional braking behavior of small BLDC speed controllers: the simple way to achieve braking capability for a BLDC motor is to short-circuit the poles appropriately to achieve desired braking force. This however creates heat in the motor, and in this case the braking might take as long as achieving maximum buoyancy: approximately one minute. The power transferred into heat is significantly smaller than the power used to rotate the motor, but it still is very desirable if the heating of the motor can be reduced by using the regenerative braking and pushing that energy back to the batteries instead of heating up the motor. As previously stated, this is most probably insignificant considering the battery capacity, but reducing heat generation is very beneficial in small, high power electronics. And it might be possible to have some impact on power consumption if the efficiency of the pump can be improved significantly and actually recover some of the energy used to alter buoyancy.

6 CONCLUSIONS

Structurally this specific AUV shall use four independent thrusters on both sides, placed in a manifold that is integrated to a spherical hull. The thrusters were tested for performance and to find out the effect of placing them inside the manifold, and it prove out that by controlling the thrusters in a suitable way the power consumption is not severely affected by the manifold structure. The maximum achievable force was also tested, and it is significantly more than the initial requirement for the design was, but as the thruster chosen is physically the same size as a lower powered one, the more powerful version was preferred in case of unexpected situations. The optional integrated speed controller was proven unreliable, and they are not intended to be used. The integrated speed controller would have been useful, because the control electronics would have been outside the pressure hull and thus saved valuable space. The choice of speed controller for the first robot is going to be replaced, as the initially used integrated speed controller prove out unreliable. A promising option is a Vedder ESC, which has worked more reliably in the testing procedures than the integrated ones, and has suitable voltage and current ratings, and in addition it is capable of communicating over Canbus.

The submarine needs to be able to operate at least five hours on the battery power, so power consumption must be kept as small as possible. Therefore, it is reasonable to compare energy consumption in short depth transitions using buoyancy control or vertical thrusters. For controllability, the vessel will have vertical thrusters regardless of the buoyancy control. Assuming the starting point of a depth change is neutral buoyancy and zero velocity, we can either change the volume of ballast tanks, wait to reach the desired depth and change the volume back to neutral buoyancy, or we can run the vertical thrusters as long as the desired depth is reached. These operations consume energy, but they do it differently, as power consumption of thruster-powered movement is directly related to the distance travelled, while controlling the ballast takes the same amount of energy regardless of the distance. Instead, the energy needed for changing the volume depends on the depth of the submarine, because the ballast pump has to work against the surrounding pressure. The other thing that matters when moving by altering the volume is the desired speed of vertical motion, because that affects the required amount of change of volume. Naturally, the less volume has to be changed, the less energy is consumed, but also the slower the vertical movement will be. This is a optimization task that needs to be done after the navigation systems are finished and the power consumption of all the continuously running electronics is known.

Because the energy usage of the thrusters does not depend on the depth of the robot, it is fairly simple to simulate the energy consumption of vertical motion as a function of desired depth transition, assuming the vertical thrusters are run at speed of optimal efficiency and that power is used until the braking point is reached. The power consumption of ballast system usage is only dependent on the external pressure at the time of increasing of buoyancy. This means the same amount power is used when moving upwards from a certain depth and when going downwards and stopping to that same depth. Previously a chart of the energy usage with different vertical control systems was presented, and it should be used as a principal guide for selecting the method for vertical movement. It shows the lower energy consuming way to move a known vertical distance, but knowing the distance might be problematic when exploring unknown areas of a mine. Under uncertainty, it is probably best option to use thrusters and perhaps adjust the buoyancy slightly to achieve a safe velocity to map the unknown area and use ballast control when the area is mapped and the distances are known. The dynamics of the buoyancy control system are very slow, thus controlling the movements of robot using solely buoyancy control will be very challenging for the control system. Approximately one minute delay from full lift to neutral buoyancy means that the control system should be able to predict the upcoming movements for that time in order to maintain minimum power consumption. This is more a problem for the control system development, but the time could be reduced by using more powerful hydraulic unit. That would require more space, which is one of the most important aspects in the robot and in this case keeping component size in minimum is more important than fast response of the system, and some other properties have to be compromised in favor of size. The problems caused by slow dynamics can also be at least partially bypassed by using thrusters, for example a short horizontal movement can be done using thrusters to keep the depth constant while maintaining negative or positive buoyancy unaltered during the time of horizontal movement. After the horizontal travel the vertical thrusters can be stopped and the buoyancy is still the same as before the horizontal part of travel.

It is also possible, and probably useful to slow down the vertical movement created by buoyancy control using thrusters, and after the robot has stopped the buoyancy can be fine-tuned to neutral buoyancy. This significantly reduces the time needed to stop vertical movement and helps position the robot more accurately compared to slowly reducing the buoyant force to zero and waiting for the drag to stop the motion. More precisely the optimal combination of thruster and buoyancy control usage must be defined as the development of the control and navigation systems goes further; the capabilities of the control system define how effectively the benefits of these different vertical control systems can be achieved.

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