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Development, Implementation, and Testing of a Reversible Master/Slave Control System for a Non-Buoyant ROV and USV

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ABSTRACT

CONTENTS

ABBREVIATIONS

Abbreviations used in the report listed in alphabetical order.

- **CFD** Computational Fluid Dynamics
- **CoG** Center of Gravity
- **NTNU** Norwegian University of Science and Technology (Norsk Teknisk og Naturvitenskapelig Universitet)
- **PD** Proportional-Derivative [controller]
- **ROV** Remotely Operated Vehicle

CHAPTER

ONE

INTRODUCTION

1.1 Marine Plastic Pollution

Marine plastic pollution is a widely documented issue. The exact amount of plastic is not known. The World Economic Forum (2022) estimate there to be betweel 75 and 199 million metric tons of plastic waste currently in the ocean, while Jambeck et al. (2015) estimated that the annual release in 2010 alone was between 4.8 and 12.7 metric tons. According to Isobe and Iwasaki (2022), most plastic types sink, however the majority of research on marine plastics is done on floating surface plastics. This means that the majority of the pollution is both unknown and unhandled.

There are two major paths for health effects from plastic pollution, larger pieces being broken down into microplastics which then get taken up into the food chain, and material leeching into the surrounding seawater. Once microplastics have entered into the foodchain, leeching becomes a concern within creatures as well.

Leeching refers to the chemical breakdown of materials going into solution, or compounds moving from one carrier to another. For example, bisphenol A (also known as BPA) is a material commonly used in polycarbonate production. Rochester (2013) show in a meta-review that Bisphenol A can affect the endocrine system of humans, especially fetuses and infants. These materials can with certain types of exposure, such as mechanical abrasion or acidity, leech from their polymerized form into the surrounding water. Other researchers, such as Sørensen et al. (2023) show that some chemicals associated with rubbers and elastomers have a toxic effect on certain marine microalgae. **?** also shows the negative effects of crude oil on haddock roe and larvae. In short, plastic leeching has been shown to impact the health of both humans and other living things.

Microplastics on the other hand, refer to small particles of plastics, less than 5mm in size along their longest axis. Microplastics might be broken up from larger pieces, for instance by wave motion grinding waste against the seafloor or against each other. Microplastics might also be released from products that include them intentionally, for instance certain exfoliating soaps or polishing compounds use small plastic beads to do the polishing/exfoliating work. The negative health impacts of microplastics both on human and animal life have been shown, for example by Segovia-Mendoza et al. (2020) and Zolotova et al. (2022). Filtering out microplastics is very difficult due to their small size clogging filters and other filtering methods quickly. One of the best solutions for dealing with microplastics is to simply avoid them being created and released. The release of microplastics is not something this report will go further into, but removing larger plastics from the seafloor would effectively halt their breakdown and further realeasing of microplastics.

The above demonstrates the health effects of marine plastic pollution, but additionally there is the concern that the physical presence of plastics might harm or inhabit marine life. Ghost fishing for instance, is a large concern from an ecological perspective. Ghost fishing refers to when tools such as fishing nets or pots are lost at sea but continue to drift, allowing them to catch animals that end up harmed or dying without human control. Matsuoka et al. (2005) goes into the issues of ghost fishing in greater detail and explains more fully how and why it is an issue.

1.2 Previous work

When it comes to

1.3 Remaining work

1.4 This report

CHAPTER

TWO

PROBLEM STATEMENT

2.1 Previous project work

The specialization project focused on making the framework for this thesis and for further work on the Plan Sea project in general. In this section, the results of the specialization project will be presented as it forms the basis for further work.

Originally, the goals of the specialization project were as follows:

1. Create a simulation to be used in later work
2. Validate the performance of the simulation
3. Create a rudimentary control system for the simulation that can be further developed later
4. Do basic research that can be implemented in this thesis

These goals were achieved with great success. Here is a short summary of each goal and its results.

2.1.1 Creating the simulation

The simulation framework AGX Dynamics was chosen based on a recommendation from a professor based on its ability to do wire simulations well, in addition to it having both a hydrodynamic simulation package and a package that could interface with ROS2. It was considered to build a simulation from scratch, but this was deprioritized due to the amount of work this would pose.

The two vessels are simulated as simplified shapes, the surface vessel as a coarse model, while the ROV is simulated as a simple box. The simulation is mostly unchanged from the original setup, though some additional work has been done and this is further discussed in section 3.1.2

2.1.2 Validating the simulation

The simulation was validated by comparing the tension measured in the tether to a calculated drag force that would be expected. The surface vessel would be moving at constant speed and the ROV dragged behind. This was done at several speeds, and the tension was measured both on average and over time. The measured tension was then compared with a manually calculated drag force using the drag equation. The simulation was found to perform within ±20% of the calculated drag, which given the assumptions made was concluded to be well within reasonable limits. Further discussion of this can be seen in section 4.2 of the specialization report **?**

2.1.3 Creating a control system

A control system is a simplified abstraction of all the logic that is behind actually controlling a system. A "system" in this sense is any collection of real-world, digital, chemical or mechanical parts that accept some sort of affecting input and provide some resultant output. In this case, the movement of the vessels are the system of interest. The inputs of the system is the commands given to thrusters, cranes, or other means of moving the vessel, while the output of the system is the physical movement of the vessels and their components in space.

The control system which was created in the specialization project was implemented directly in the same script as the simulation ran on. This was not ideal, but it did work. As it was implemented, it could control both the heading of the vessel towards its waypoint as well as its total force applied. It was implemented as navigating to a list of points, changing to the next point after it reached some steady state around the current one. The movement of the ROV and crane was not controlled in the control system achieved in the specialization project.

As mentioned, the control system was not implemented in ROS2, as was the plan. This was not done due to issues with initializing a ROS workspace and decoupling the work already done. This has been achieved in this project however, and is further discussed in section 3.1.2.

2.1.4 Basic research

2.2 State of the Art

2.2.1 Physical issues

2.2.2 Simulation issues

2.3 Mathematical basis

2.4 Modelling and Control Design

2.5 Sensorics

The first step to knowing where to go is knowing where you are.

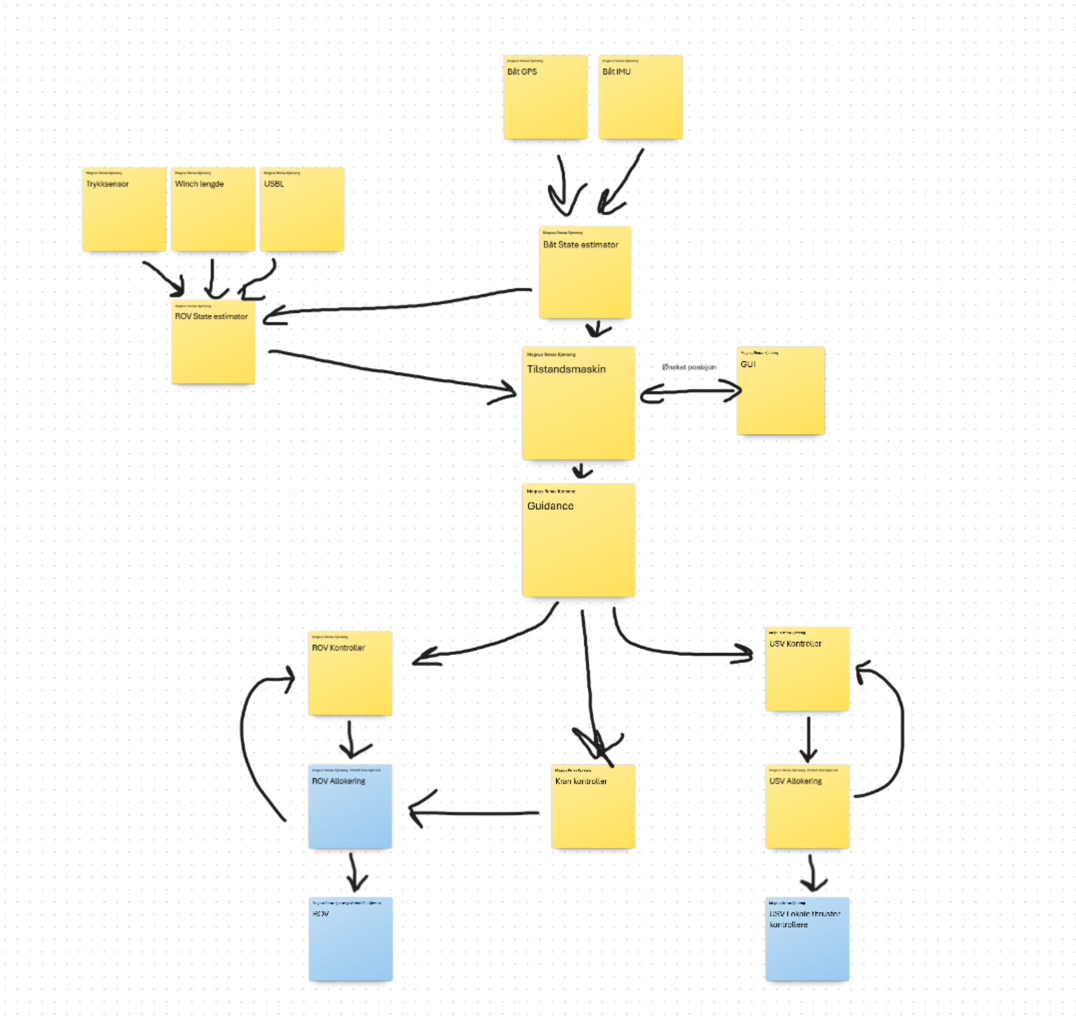

Figure 2.1: A sketch of the control system design. TODO: Fiks bedre illustrasjon

There are several pieces of sensorics that will be used for positioning of the system.

2.5.1 GNSS

Firstly, Global Navigational Satellite Systems, or GNSS, will be used to position the USV. There are several separate systems for GNSS, including GPS, Gallileo and GLONASS to mention a few.

The exact workings of how GNSS works is not essential for this project. The important part is that GNSS requires a clear view of the sky and allows for accuracies of approximately 2m. While this accuracy would be usable for this project, a higher accuracy would be preferable. Luckily, there exist systems that allow for this greater accuracy as well. For this project, an RTK enabled GNSS reciever has been acquired. RTK uses a secondary base station and direcct communication between the receiver and the base station to produce highly accurate readings, on the order of millimeters or centimeters, as opposed to meters.

GNSS requires a clear view of the sky, this means that it's not usable indoors to a large extent, and it's also not usable under water. Water is an excellent absorber of the entire spectrum of electromagnetic radiation, from radio all the way to gamma rays. This means that separate positioning is required for positioning the ROV.

NMEA-0183 GGA message used for recieving position

2.5.2 USBL

The main method for positioning the ROV will be through an ultra-short baseline system, USBL. USBL works sonically by having a tranciever on the surface vessel which transmits a sound signal, the signal is picked up by a transponder under water which transmits a response signal. The tranciever through an array of hydrophones picks up the response and is able to find the direction it came from as well as the distance. Direction comes from differential time of response for the different hydrophones, while distance comes from a combination of time-of-flight and doppler (TODO: sjekk om doppler faktisk er en greie her).

TODO: Legg inn figur av USBL

Available and accurate

Need to consider limitations of accuracy of USBL re: salinity, water temperature/density, etc.

2.5.3 IMUs

Both the surface vessel and the ROV will have inertial monitoring units, IMUs, installed. These detect changes in velocity and acceleration in 6dof, allowing for relative position to be found. IMUs are most useful as a dead-reckoning tool, i.e. using a last known location and a set of velocities/directions, an approximate current position can be found.

For this solution, the IMUs will be used as supplemental data to the USBL and GNSS systems. This is to allow for a more complete model of the movement of each of the vessels. Especially for the surface vessel, things like heave from waves is not necessarily easy to get from GNSS data, but will be trivial to find from an IMU. Using this it's also possible to potentially build a model of the current seastate which allows for better predictive DP rather than just a reactive system which is what's currently implemented.

2.5.4 ROV Depth measuring devices

The ROV will have a couple of extra sensors for finding depth and distance from the seafloor.

A pressure sensor is able to fairly accurately (within 1m) tell the depth of the ROV. Pressure sensors can work in many ways, the ones available here use a two chamber differential approach with a flexible membrane between two chambers. One chamber is open to the atmosphere and the other is closed off with a known pressure inside. By measuring the amount the flexible membrane stretches, it is possible to find the pressure differential between the two chambers. Knowing this differential and the calibration pressure, it's possible to estimate the depth by using the knowledge that water pressure increases by approximately 10kPa per meter of depth. More accurate values can be found but depend on things like water temperature, salinity and others.

Another tool which will give an upper bound to the depth of the ROV is the length of wire which has been payed out. Due to effects because of lag and currents as mentioned previously (TODO: faktisk skrive dette) the length of the wire will in most cases be greater than the actual depth of the ROV or the distance to the ROV. It can still be useful to know this length though, both as an absolute upper bound to fact-check the other sensors, but also to keep track of how much of the wire remains and how the winding system may work.

Additionally, the ROV will be mounted with a laser based time-of-flight sensor. This sensor works similarly to the USBL system mentioned above but using laser light instead of sound. A laser is sent from the sensor, hits obstacles or the seafloor and bounces back. The light bouncing back is detected by the sensor and doing time-of-flight calculations, it's possible to find the distance from the sensor to the object in question. This can be done to very accurately measure the distance to objects or the seafloor to avoid collisions or aid in picking them up.

Another example of something that could potentially help is taut wire positioning. Taut wire positioning works by having a wire anchored at a given point and then measuring the angle at which the wire exits a boom or whatever is holding it in place. By knowing the length of wire, the fact that the wire is taut, and the angle at which the wire is extending from the surface vessel, it is possible to find a relative position between the surface vessel and the anchor. It is possible that with a very heavy ROV, or if the ROV picks up a large load, that taut-wire might work for positioning, but given the effects on the wire seen in simulation it's very probable that taut-wire will provide more trash data than useful. Due to this it's disregarded as an option.

2.6 State estimation

The state estimator takes in the various sensor data and builds a single model of position. This is done because different sensors might have different accuracies or update times. The state estimator handles these discrepancies and builds a cohesive model. The state estimator feeds this more accurate position into the guidance system (TODO: Spørre øivind om det er guidance eller state machine som får posijonen. State machine skal jo bare være et informasjonslager?)

2.7 State machine

The state machine keeps track of variables for the total control system. These include current position, but also things like desired position or operating mode, gathered from the GUI.

2.8 GUI

The GUI is where a human operator interfaces with the control system. The GUI is supposed to include a position input for the surface vessel, mode switching between USV-Master, ROV-Master and idle/standby modes, along with other functions.

2.9 Guidance

The guidance system provides finer control of the vessel than what would be achieved by a state machine and controller alone. For instance it smooths acceleration/deceleration of the vessels by providing imaginary set points between the current position and the actual set point.

2.10 Controller

The controller finds a desired force input based on the difference (error) between the current position and the desired position. The current implementation uses a simple PID for this. This force input is fed forward to the allocator.

The shape of the force coming out of the controller is as

$$\tau = \begin{bmatrix} X \\ Y \\ N \end{bmatrix}$$

2.11 Allocation

The allocator works like a translation layer between the controller and the local controllers. The controller provides a force input on the vessel's center of gravity. By inputting forces on the center of gravity, no torques are produced from lateral forces, nor lateral forces from the torque.

In abstract terms, the allocator finds and applies a transformation matrix T such that

$$Tf = \tau$$

where f is a vector of vectors with the lateral forces for each thruster. For this case with two thrusters, it will look something like

$$f = \begin{bmatrix} x_1 \\ y_1 \\ x_2 \\ y_2 \end{bmatrix}$$

The transformation matrix can be written explicitly for the USV, since it has a very simple thrust configuration. For larger configurations it might be better to write each thruster's transformation individually and either add or remove them depending on the type of move necessary (larger moves use only larger thrusters etc.).

$$T = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ -l_{y_1} & l_{x_1} & -l_{y_2} & l_{x_2} \end{bmatrix} \tag{2.1}$$

Since τ and T are known, we can find f by performing a pseudoinverse on T leading us to the equation

$$f = T^{\dagger}\tau \tag{2.2}$$

where $T^{\dagger}$ is the pseudoinverse of T.

This can also be written longform as

$$\begin{bmatrix} x_1 \\ y_1 \\ x_2 \\ y_2 \end{bmatrix} = T^{\dagger} \begin{bmatrix} X \\ Y \\ N \end{bmatrix} \tag{2.3}$$

The full matrix for $T^{\dagger}$ is omitted because the pseudoinverse of a non-square matrix tends to be large and ugly. It will only be handled by machine hands anyway, and as such doesn't matter right now.

The ROV has a built-in allocator which works well enough. The only issue with the ROV's allocator is that it's configured for a neutrally buoyant vessel. For this system we need to filter the vertical force component so the ROV only handles high-frequent/small-amplitude responses and the crane handles larger amplitudes and lower frequencies. This is also necessary because of elasticity in the lifting cable.

2.12 Local control and physical response

The vessel in this iteration has two thrusters. The ROV has a closed working solution and will not be considered here except for in the hypothetical. Each of these local controllers receive a two-component vector (or three-component in the case of the ROV) which instructs the controller what the desired thrust is. The azimuth thrusters on the USV are able to apply a force in one direction (parallel to the propeller axis), but they are able to vector this one-dimensional thrust using the azimuth ring.

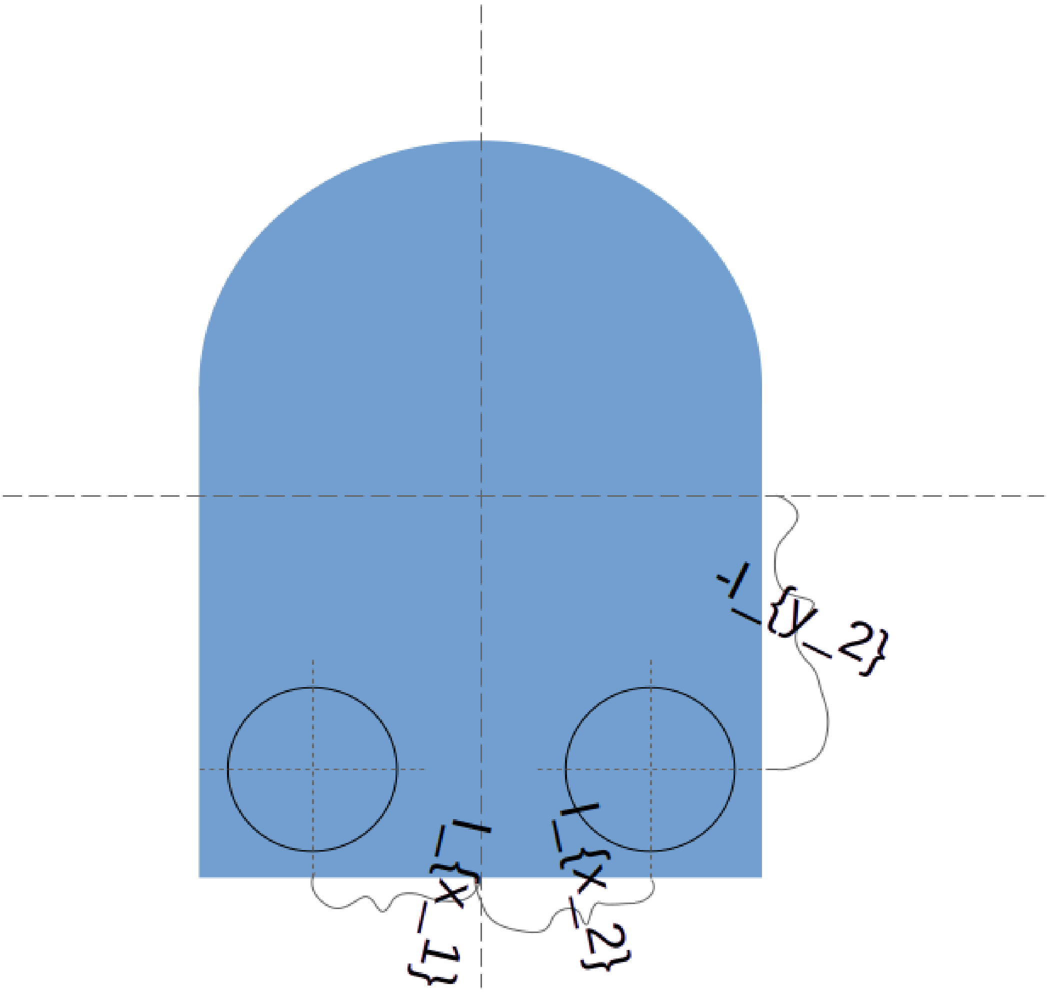

Figure 2.2: Sketch of how the thruster position values in eq. (2.1) are found. The thruster configuration will be input to the allocator through a config file.

CHAPTER

THREE

DESIGN

This project can be very broadly divided into two segments, the simulation segment and the physical testing segment. The goal is that the simulation is to be as true to reality as possible. With a true-to-life simulation, a control system can be built to work in the simulation. Once the control system is created and tested satisfacotrily, it can be "transplanted" to the physical test. Because of these two different segments, I will talk about them separately.

Another way to look at this is as an agnostic control system and a plant, where the plant is implemented both as a simulation and as a physical vessel. Which alternative is better is hard to tell right now so both are included.

3.1 Simulation framework

The simulation was implemented in Algoryx AB's AGX Dynamics, a seemingly solid simulation framework which is able to simulate both the hydrodynamic effects on the vessels, as well as the wire dynamics etc. on the tether. A license for AGX Dynamics (from here just AGX) was also available within the university making implementation easy.

The exact details of the implementation are more specifically brought up in **?**, the specialization project completed as a preparation for this thesis. Below is a brief explanation of the simulation setup.

3.1.1 Brief simulation setup

The two vessels to be simulated are the surface vessel and the ROV. The ROV was simplified as a cuboid with the proper dimensions according to the manufacturer's specifications. The ROV to be used is a modified BlueROV2 Heavy made by Blue Robotics. The dimensions of which are 575 x 254 x 457 mm (WxHxD). The density of the ROV has not been tested, but is implemented in the simulation as $2000 kg/m^3$. This is a rough estimation and the real density is likely lower.

The surface vessel was modelled roughly in CAD and then exported as a `.obj` 3D-file for AGX to work with. The dimensions and shape of the vessel are roughly corresponding with the real vessel, though not exactly as it was intended to be exchanged for a more detailed model produced by a different master project at a later date. The density of the surface vessel is implemented at $600kg/m^3$ which was arrived at by taking a rough average of the different densities of sandwich plate we had for building the hull and then adding some extra mass to account for batteries, sensorics and other added weights.

As a note on the densities of the vessels: while AGX is able to model non-uniform densities and varying density distributions, this was not implemented in this simulation simply for the constraint of time. It was assumed that the loss of accuracy from assuming uniform density is small enough not to matter.

Since the ROV sinks it needs help staying afloat. This is achieved by a tether connected to the surface vessel. The tether is modelled as a non-buoyant rope/wire with a radius of 10mm and a Young's modulus of 10^9. These figures are all assumed values and should be updated when the real values from the real version are found.

The two vessels and the tether are placed in a 200x200x100m pool of water. It is possible in AGX to simulate different sea-states, but currently implemented is a calm sea, meaning the only hydrodynamic effects are those brought on by the movement of the vessels.

3.1.2 Improvements made since specialization project

During the specialization project, it was not possible to implement the simulation as one decoupled from the controller. As such, the end result was that both the controller and the plant were running in the same simulation script. This has been improved upon now as the controller and its parts has been separated from the simulator and are now running as separate nodes commuicating via ROS2. The full ROS2 graph can be seen in **??**. Decoupling the simulator and the various controller nodes has allowed for work to progress slightly faster and more reliably. When it is possible to more or less finish one module before working on another, it makes doing the work easier.

In addition, the simulator now is capable of simulating the winching movement of the winch on the ROV. Previously it was implemented as a fixed length wire. This means that the crane now is able to operate. A rudimentary implementation to ROS has been made as well, allowing for the speed of the winch and breaking power to be changed via ROS topics.

3.2 Physical setup

3.2.1 Surface vessel

The Plan Sea project was contacted by the shipyard Brødrene Aa, in Hyen, Norway, and asked if they wanted an introduction to composite hull construction and some free materials. The Plan Sea project accepted this and got training and materials in how to apply and build a vessel from carbon fiber sandwich boards.

The sandwich boards are built up of a central foam core clad with 3-5 layers of carbon fiber weave and epoxy. Using the foam core it is possible to achieve stronger hulls than using the carbon fiber alone would, while also being lighter than an equivalent strength hull made from only carbon fiber.

The vessel was constructed as a two-engine catamaran with rough dimensions of 2.5x2x1m. A catamaran construction was chosen due to the small size of the vessel not affording a lot of stability, a catamaran would allow for a wider hull without significantly increasing hull drag compared to a monohull construction.

Another bonus of having a catamaran construction as opposed to a monohull construction is that by simply cutting a hole in the deck between the hulls, a "moonpool" is achieved. This lets the ROV be lifted at a point closer to the center of mass for the catamaran which leads to fewer instabilities in the system and less chance of capsizing or other catastrophe.

The thrusters for the surface vessel have been made using two Torqeedo Cruise 3FP thrusters. The thrusters are fully electric and designed for through-hull mounting. This makes the modification from stationary to azimuth thrusters relatively simple. The modified azimuth thrusters were mounted to the aft of the two hulls, one in each. If this is too little thrust it is possible to mount further thrusters further forward to provide assistance, either for propulsion, DP or redundancy.

3.2.2 Subsea vessel

The subsea vessel is based on a BlueROV2 Heavy, made by BlueRobotics. The BlueROV is a prosumer-grade battery operated remotely operated vehicle. It's approximately 0.5x0.5x0.3m in WxDxH. The ROV has been acquired to use for the Plan Sea project specifically. It is not the ideal solution for this case, but it's been decided that modifying an existing and functioning solution is better than attempting to build a new one, at least for this proof of concept.

A bracket has been designed to account for a mounting point for the USBL transponder, as well as to securely mount to the ROV already in use.

3.2.3 Crane

A crane needs to be designed. Thsi can be done as simply as possible having just a simple A-frame crane mounted over a moon pool. The crane system needs to consist of a few different parts. The gantry/frame itself, a winch motor, a winching system for the ROV tether and a winching system for the ROV lifting wire.

3.2.4 Control systems/Ancillary

the entirety of the control system will be acting as one big system divided into many smaller parts. The fact that ROS allows for multiple subscribers and publishers to various topics means that each element can have its own local controller that only interacts with the others. This means that the surface vessel, the crane and the ROV will all act as independent parties in the same system.

3.2.4.1 ROV control

The ROV's control system is based on an ArduPilot implementation. ArduPilot is an open-source autopilot system which is intended to be used for any remote or unmanned vehicle. The current implementation needs to be modified to allow for the type of control that's required for the project.

The majority of heave-movement will be caused by the crane onboard the surface vessel, rather than the thursters on the ROV as it's set up for by default.

3.3 Case description

CHAPTER

FOUR

SIMULATION CASE STUDIES

CHAPTER

FIVE

RESULTS

5.1 Simulation results

As mentioned in previous chapters, the simulation was a continued work basedon a specialization project which was undertaken in the fall semester of 2024. The goal of the simulation was to simulate the physical situation to allow for tuning and development of the controller. As such, using the commercially available simulation framework AGX Dynamics, developed by Algoryx AB was seen as reasonable.

AGX Dynamics is used as a simulation framework for both machine-in-the-loop systems as well as for simulation of dynamic systems including wires, granulates and hydrodynamic/aerodynamic situations. The reasoning has been that if it's good enough for these purposes it will be good enough for this project.

5.1.1 Validation

Validation of the simulator was primarily performed in the specialization project. There it was done as both an imperical measurement as well as a more general measurement. The specialization project found that the simulator performs as expected.

As a summary of the validation, the tension experienced by the tether between the ROV and the USV was both calculated using manual methods and simulated. The calculations and simulations were performed at 6 different speeds, between 0m/s and 5m/s in 1m/s increments. The ROV was observed in the simulations to drag behind the USV, since the USV is the powered part in this validation and the ROV is only hanging behind as a passive part. As the angle of the tether changes, the cross-sectional area of the ROV as well as the drag coefficient changes. To account for this, the calculated drag was calculated at two separate drag coefficients, one for a flat-facing cuboid and one for an edge-facing cuboid, respectively chosen from tables as 2.05 and 1.05. The forward facing area was assumed in calculations to be constant, however this is an obvious simplification and source of error.

The tension calculated on the wire was compared to the tension provided by the simulator, and was found to be within an acceptable range of error. The deviation between calculation and simulation was found to be between 3% and 55%, which considering the severe simplifications assumed makes the results of the simulation seem valid. Additionally, as could be expected, the deviation between calculation and simulation changes as the speed, and thus the drag coefficient and forward facing area, changes. At low speeds, the lower drag coefficient provides more accurate results, while at higher speeds the higher drag coefficient provides more accurate results. This is likely an effect of the forward facing area changing significantly, but is consistent with the expectation looking at the simulation, that the drag increases with speed. Accounting for this change in drag with speed, the deviation can be said to be between 3% and 20%, which is definitely within acceptable ranges for accuracy.

All these elements are discussed further and in greater detail in section 4 of the specialization project.

5.1.2 Limitations

The simulator is currently not implemented with a winching motion available, and control for the ROV is also not implemented as it stands. ROV control has been implemented before while the controller was a part of the simulation script, but has not been reimplemented as ROS2 has been implemented in the system. These elements have been deprioritized in order to allow for the physical testing of the vessel and its control system. Ideally, the implementation of these elements will not be very time consuming, nor will they affect the greater system as is the goal of the node-based system of ROS2.

5.2 Controller results

5.2.1 USV

5.3 Results of physical testing

CHAPTER

SIX

DISCUSSION

CHAPTER

SEVEN

CONCLUSIONS

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