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Simulation of a coupled system consisting of a non-buoyant remotely operated vehicle and a surface vessel

Specialization Project Report, IP502122
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ABSTRACT

The project Plan Sea is a student project etc. etc.

A non-buoyant ROV is designed to hang from a USV via a cable. The ROV will pick up seafloor litter. This becomes a coupled system. This project and report has had the focus of making a simulator for the coupled system for producing an environment in which rapid prototyping of a control system is possible.

CONTENTS

ABBREVIATIONS

- **CoG** Center of Gravity
- **ROV** Remotely Operated Vehicle

CHAPTER

ONE

INTRODUCTION

1.1 About this report

This report is a summary of work done in the course IP502122 - Specialization Project, undertaken in the autumn of 2024 at NTNU in Ålesund as a part of my master's degree in Product and Systems Engineering. The specialization project is intended as an introduction and "head start" on my master's thesis next semester. As such, the work done here is used in large part as a jumping off point for later.

1.2 Marine plastic pollution

Plastic pollution in the oceans has been widely documented. The amount of plastic currently in the ocean is uncertain, however. Jambeck et al.[1] estimates that in 2010, somewhere between 4.8 and 12.7 million metric tons(MT) of plastic ended up in the ocean. According to the World Economic Forum[2], there is between 75 and 199 million MT currently in the ocean. Around two thirds of all plastics that end up in the ocean are heavier than seawater [3] meaning that they sink and either drift in the pelagic zone or end up on the seafloor as litter. Removing litter and plastic pollution on a large scale is difficult, removing it under many meters of ocean makes it much more difficult.

It is undesirable to have plastic waste in the oceans. This is because of the health effects the plastics have on marine and terrestrial life. Two points are especially of note: microplastics and leeching. Microplastics are plastic particles smaller than 5mm. Leeching on the other hand, is the plastics' chemical interaction with the seawater surrounding them, leeching harmful chemicals into the water. **TODO: kilder for mikroplast og leeching skadelighet** For both of these issues, the best solution is to remove the litter. This is because plastics' general longevity. For example, Oluwoye et al. [4] found that polyethylene, commonly used as a coating for subsea structures, would take about 800 years to degrade on the ocean floor. Polyethylene is also used in many consumer- and industrially facing applications, for instance in plastic cannisters for liquids, boxes and crates for fishing or other industrial practices, or as plastic bags.

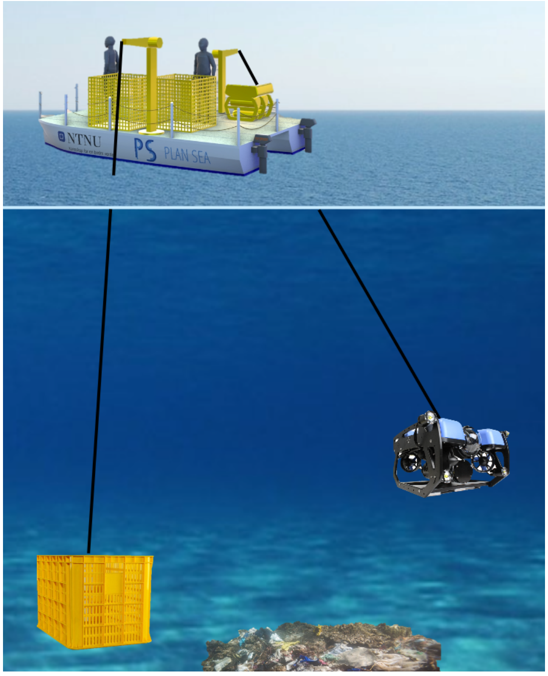

Figure 1.1: A sketch of the proposed solution for Plan Sea showing a surface vessel, a tethered ROV and a collection basket

1.3 The Plan Sea Project

The desire to deal with sub-surface marine plastic waste, i.e. litter both in the pelagic zone and on the seabed, was what sparked the Plan Sea project. Plan Sea is a student driven project at NTNU in Ålesund with the goal of finding, developing and testing a potential solution for removing sub-surface plastics. The project is at time of writing still in its early phases and ongoing.

Since this is not a report focused on the Plan Sea project, the proposed solution arrived at in Plan Sea will not be discussed in detail. However, because of the relationship between this project and Plan Sea, it is necessary to describe the solution at a surface level.

1.3.1 The proposed solution

The solution arrived at which is currently under development is an ROV-based solution with an unmanned surface vessel attached. The ROV has a gripper attached and will navigate to find litter, grab it and pick it up. The surface vessel exists to provide the ROV with a greater lifting capacity. If the ROV was to lift purely under its own force, as is traditional for ROVs, the total amount of lifting force available would be limited by the vertical thrust available on the ROV. This would mean that either the ROV would have to have a very large amount of vertical thrust available relative to its size, or that the total lifting capacity would be very small. By connecting the ROV to the surface vessel with a winch and a lifting cable, it is possible to use the ROV to do fine-navigation to find and attach to litter, and then use the lifting force of a winch and the total buoyancy of the surface vessel for lifting heavier objects. Additionally, the solution is supposed to have an undersea basket for collection to avoid the ROV needing to do the surface-bottom roundtrip for each piece of waste. A sketch of the solution can be seen in fig. 1.1.

Using this solution allows for completely ignoring the buoyancy of the ROV, unlike traditional ROVs. Traditional ROVs are generally designed to be neutrally buoyant, meaning that they neither sink nor float, but keep their vertical position in water once placed there. Since the Plan Sea ROV will be attached to a cable to the surface vessel at all times, it can instead hang from the cable. This means that it's possible to attach larger grippers, more battery capacity, more detection/lighting/navigation equipment, and otherwise allows for pretty much whatever is desired to be done to the ROV. Additionally, since the ROV doesn't need to provide vertical thrust, it is much easier to not disturb the seabed which will provide a clearer view for detection equipment based on visible or near-visible light. However, having a non-buoyant ROV does come with some drawbacks.

One drawback of this solution is that it will switch between two operating modes, searching/grabbing and lifting, increasing the complexity of the system. Another drawback is that as the ROV is hanging from the cable, it creates a coupled system consisting of the surface vessel and the ROV, and necessitates the two moving together as one unit.

This project is focusing on how to control the two units as one.

1.4 Control systems

A control system commands and regulates the behaviour of other systems automatically. For this project in particular, the control system will be in charge of maintaining and changing positions of the surface vessel and the ROV.

1.4.1 Considerations because of a coupled system

In the marine sector, dynamic positioning (DP) is commonly used. DP allows for a vessel to maintain a position or a course automatically despite external effects. This is used for example for offshore supply vessels which need to stay stationary relative to an anchored platform to allow loading and offloading of supplies. DP is also used for applications such as laying subsea fiberoptic cables, where maintaining correct speed and course is important to avoid damaging the cables. For the Plan Sea project too, a DP system is necessary because it consists of vessels that need to maintain specific positions at sea with wind, wave and current forces affecting the vessels

Normally a DP system only considers one vessel, however for the Plan Sea project it has to be more comprehensive than that because the two vessels are coupled.

1.4.2 The need for rapid prototyping

Rapid prototyping is a concept used increasingly as time goes on. The point of rapid prototyping is to create some simulated environment in which you can test and iterate on a solution until it is acceptable, before putting materials and resources into building and implementing the solution in the real world.

For my purposes, rapid prototyping will allow me to experiment with control system tuning and variables without having to deploy the full-scale vessel every time. Ideally, the solution arrived at in the prototyping stage will be directly applicable to the full-scale version, which allows for rapid deployment and only some interfacing issues to solve in the field, rather than larger issues. **TODO: Omformuler det her**

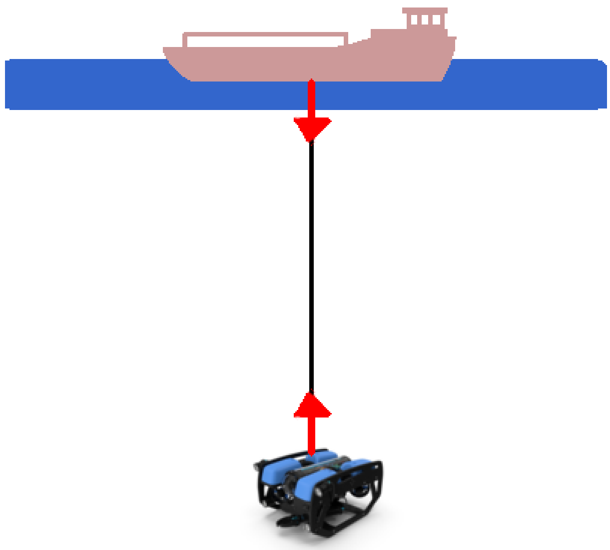

Figure 1.2: A simplified sketch of the problem, forces experienced by each vessel are shown in red.

1.5 Problem description

A simplified sketch from fig. 1.1 can be seen in fig. 1.2. It shows the three main components of this system: The surface vessel, the ROV, and the tether between them. It also shows the forces in the tether. As the tether holds the ROV up, the tether pulls the surface vessel down. This follows from Newton's second law of motion. The figure also shows the coupled nature of the system, since the tether will be taut at all times, both vessels will

In fig. 1.3 two scenarios are shown at the same time, one where the ROV is hanging straight below the surface vessel and another where it is at an angle. The result is that the ROV is not at a constant height. If we imagine a desired elevation above the seafloor is constant, then either the ROV needs to have more tether payed out and provide lift through its own thrusters, or the surface vessel needs to move to allow the ROV to hang perpendicular to the surface of the sea. If more tether was to be payed out, if the system then stabilizes with the ROV at the lowest possible point, it is possible the ROV might collide with the seabed. The ideal solution then becomes that the surface vessel follows the ROV, or the ROV only operates within a given area of operations directly underneath of the surface vessel.

Further, this non-perpendicular arrangement will lead to tangential forces, shown in fig. 1.4. The forces will of course be mirrored on the vessel's end, but this has been omitted from the figure for clarity. The horizontal force the tether imparts on the ROV will act as a restoring force, trying to move it back to be perpendicular to the surface vessel. The surface vessel likewise will experience a pull towards the ROV.

Because these two vessels are connected and so dependent on each other's positions, the control systems of each need to take this into account. Probably, the simplest solution will be to have one large control system handling both, or alternately having one of the vessels take a leading part and the other attempt to follow.

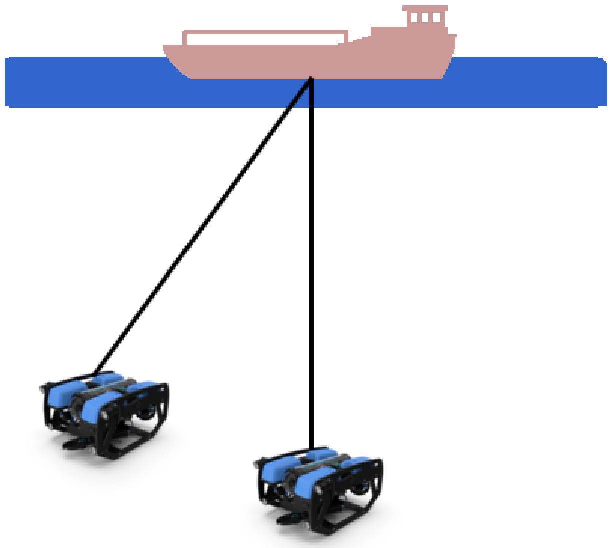

Figure 1.3: The ROV is hanging from the same point on the surface vessel with an equal tether. Note how the height of the ROV has changed because the tether has stayed the same

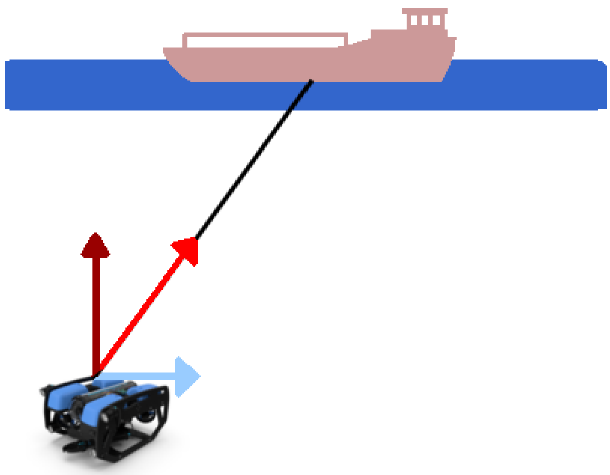

Figure 1.4: The component forces on the ROV resulting from an angled lift, decomposed

1.6 Statement of intent

For this project I want to create a simulation which is able to quantify the effects that the parts of the system have on each other. I want to be able to measure the tension in the wire, the force exerted by the vessels, how well the vessels follow each other or orders given and

The stated intent of the project this report is for is to create a simulation of the coupled system consisting of the surface vessel and a subsurface non-buoyant ROV. This simulation should be controllable and configurable to allow it to as best as possible match the real-world vessels. Ideally the controllers used in the simulation should be directly transferable and applicable to the real-world implementation.

CHAPTER

TWO

MODELLING AND CONTROL DESIGN

2.1 Literature review/State of the art

There is little specifically helpful literature on the topic of coupled powered systems above and below the surface of the sea. There are however bits and pieces that are useful. Primarily, the offshore oil and gas industry, as well as general ROV operations are able to help a bit. The main issue with this project and its challenges is that it is a form of combined system. There are several papers discussing for instance the effect of currents on deep-submergence suspended tooling used for oil and gas installations. For example, Lian and Sortland 1996 [5]. They also performed simulations, however their paper is focused on non-powered remotely operated tooling (ROT) as opposed to a remotely operated vehicle. Their results can be useful as a kind of sanity check for the results of the simulations of this project, though their working area is down to 1500m below the surface while it's improbable that the Plan Sea project will ever operate below 200m.

The tether is also a consideration for this project, Chen et al. 2021 [6] discuss the hydrodynamic effects on ROV tethers under complex sea conditions. Whether or not this is useful for this implementation is uncertain, as the tether simulations are all done by the simulation software. It might be possible to expand the tether simulations to include Chen et al.'s findings, but this is not done at present.

Enevoldsen et al., 2018 [7] provide one of the more useful documents on the topic. They discuss a simplified modelling strategy for ROVs to allow for both greater control capabilities and simulated efforts. The state of this project has not used this information, but it will be very helpful in later iterations to expand the accuracy of the simulation for the ROV, both for control purposes and for a more accurate simulation. Anderlini, Parker and Thomas 2018 [8] discuss control of an ROV carrying an object. They discuss the sudden added mass of the vessel and how to compensate for it from a control perspective, though their paper focuses more on autonomous underwater maintenance vehicles. This paper as well will be very helpful for further implementation work, but has not been used in any great extent here. Thingstad and Hveding, 1982 [9] have a conference paper on non-buoyant ROVs for performing subsea work. On the surface this sounds perfect, but looking into the paper it is more focused on the physical construction of the ROV rather than the control of it. This makes it less helpful for me. Additionally, Thingstad and Hveding's paper is more than 40 years old at time of writing, and applications of control theory, as well as microelectronics and actuators have evolved a lot since then, making what little control they do discuss less useful. Their paper is still mentioned here for completeness.

2.2 Mathematical basis

The root problem can be decomposed into equations 2.1 and 2.2. They show the forces that impact the motions of both the surface vessel and the ROV. The forces that have an impact are hydrodynamic forces, such as buoyancy, righting moment etc. The propulsive forces that the vessels' thrusters provide. Environmental forces coming from waves, winds and currents. And finally the force the coupling acts with on each vessel. Do note that though the form of the equations is the same for the surface vessel and the ROV, the values both in total and in each individual element are not going to be equal. Hydrodynamic, propulsive and environmental forces will be entirely individual for each element because of their physical shape and capabilities. The coupling forces however will be linked to each other, though not directly because of how hanging wires act. See **??** for elaboration.

$$M_{v_{\text{surf}}} = \sum f = f_{hydro} + f_{prop} + f_{env} + f_{coupling} \tag{2.1}$$

$$M_{v_{\text{ROV}}} = \sum g = g_{hydro} + g_{prop} + g_{env} + g_{coupling} \tag{2.2}$$

The equations demonstrate the need for simulation compared to analytical examination of the problem. Hydrodynamic forces and environmental forces contribute to a highly dynamic system that is difficult or impossible to find a closed form expression of. This means that calculating an expected state for the dynamic system manually is labour and time intensive. Using a simulation instead of analytical methods hides these problems away. The simulation will take care of the complex interactions which allows me to focus on extracting interesting data. I will further discuss simulation options in chapter 3

Using a simulation does introduce a new requirement: that of validating the models' accuracy. There are many ways of doing this, both intuitively and mathematically. I will get into these in **??**.

The simulation allowing for "setting and forgetting" whatever parts of the force equations are desired allows the user to focus on whatever specific field they are interested in. For example a user might examine the propulsive force required given a certain seastate, or how hull shape and hydrodynamics affects the stability of the total system.

2.3 Control theory?

This project is primarily focused on simulation and control. As such I will give a basic introduction to control theory here.

Control systems are systems that control other systems. For instance a dynamic positioning system is a control system that controls the vessel's position. The "other systems" are usually called the "plant".

CHAPTER

THREE

SIMULATION FRAMEWORK

The goal of this specialization project is to build a simulator which is applicable to the case of the Plan Sea project. There are five elements that need to be simulated for this to be considered a success.

- Surface vessel
- Subsurface vessel
- Connecting wire
- Weather impacts
- Control system

Of these points, all of them can be simulated fairly simply with purely analytical methods except for the connecting tether. Wire physics are a notoriously difficult thing to simulate because they are not rigid bodies. They have strength in tension but not in compression, leading to a discontinuous behaviour. You can't push a rope, or wire in this case.

There are two main paths to take with regards to making the simulation. I could make everything from scratch from first principles or I could use an already existing simulation framework and build something on top of that. Both solutions have positives and negatives.

Creating a system from scratch would be an interesting challenge. It would also give me exactly the results I'd want with very little overhead, assuming that my own programming skills are up to the task. The bespoke, home-made simulator also wouldn't have any associated licensing costs. On the other hand, to create a simulator which includes buoyancy, fluid dynamics, wire physics, handles a coupled system and also has some form of graphical interface/readout for the user is a large task to undertake.

Using a commercially available system also has a fair few benefits. I would have a mostly ready-made framework which I can just configure the simulation at hand within. Changing out parameters and variables would also be very simple, as it's essentially the same as the original configuration. I believe also that the results from a commercial solution would be more reliable than my own attempt. It is reasonable to assume that an industrially used simulation solution made by a team of physicists, computer engineers and other specialists is fairly accurate with regards to its results. The same cannot be said for a cobbled-together solution made by one student in roughly 6 months. Commercially available solutions are not all perfect however. There are licensing costs associated with many simulation frameworks. Some having enormous costs for the scale of a student project. There is also likely more overhead with a commercially available solution due to them being as wide in their application as possible, to allow for as many customer types as possible. This can make the commercially available solution slower or less responsive.

After considering the points above for both commercially available and personally crafted simulation frameworks, I decided that using a ready-made solution would be better. This was especially decided because of the time constraints of this project. My goal is to have a working simulation that can be used to provide information, the goal is not to make a simulator. If I was to make it myself, the project would quickly turn into "make a simulator" rather than "make a simulation", simply because of the scale of the undertaking.

3.1 AGX

After considering multiple simulation options and on the advice of a professor, I landed on using AGX, made by Algoryx, as a simulation framework. AGX has a solid wire simulation package, a hydrodynamic simulation package, and allows for scripting and setup using both Python and C++. It has interfaces towards both Unreal Engine and the Unity engine for further graphical display of the results. In addition, AGX has interfaces for ROS2 which I will get into in section 3.3.

My implementation of AGX is based on Python as that's the language I'm most familiar with. I am aware of Python's inferiority to a C++ based approach in terms of speed and efficiency in resource use, but the time investment required for me to get to an acceptable level of C++ proficiency was not worth it for this project.

3.1.1 Limitations of AGX

By using a ready-made simulation platform I am able to quickly implement a simulation without needing to worry about the mathematical models that exist behind the simulation. This allows me to focus on achieving results, although it also necessitates a degree of trust in the simulation. I am able to verify whether the simulator acts as expected or not, but changing the governing equations is not necessarily something I am able to do.

Another limitation of AGX is that it's a licensed software. This means that in order to apply and use the findings of this report, the software needs to be acquired. This is a limitation for further research, and ideally the findings should be based on open and available software or arrived at from first principles.

3.2 Description of the simulation setup

The simulation starts with defining a water volume. This is done using AGX built-in functions. Currently the volume is 100m along the sides and 50m deep, though this is arbitrary. I've implemented one "water controller" which is the object that handles wave, current and wind forces. Currently this controller is completely still and there is no force inputs, but it is implemented so that adding weather forces is simple for later iterations. In AGX, each element in a simulation has to be individually added to that simulation.

Once both the water volume and the water controller have been added to the active simulation, the vessels are made.

The surface vessel and the ROV are both implemented as children of a parent class for general vessels. I've done this for ease of expansion later. The ROV is just a simple box with a given density and size. The ROV's size I've taken from BlueROV's websites, as an example of the size of ROV we will be working with in this project, though as mentioned it's just implemented as a box. The exact dimensions are 0.45m x 0.575m x 0.254m for a total volume of $0.0654m^3$. If a more accurate shape for the ROV is desired, it is possible to implement it similarly to the surface vessel, but since this project is mostly a first-order approximation of the problem, I believe a simple box is sufficient. The ROV's density I have wildly exaggerated and arbitrarily chosen to be $2000\frac{kg}{m^3}$. This is an absurd exaggeration and should be replaced with more relevant data later, but for a proof of concept it will work fine. This gives a total mass of the ROV of 131kg. The surface vessel's shape is defined by a wireframe stored in an `.obj` file I've made that approximates the shape of the hull, while its density I've approximated from the density of the carbon-fiber sandwich board used to $600\frac{kg}{m^3}$.

In addition to a class which handles the shape and properties of the surface vessel, I have made a class that handles controlling the surface vessel for now. The controller is just a simple implementation of a PID controller and is not properly tuned yet. The controller checks the position of the vessel on each timestep and calculates an error. The error is then controlled using the PID controller and a response is found. The response is clamped within a given authority limit. I've done this because realistically, the control authority of the system is going to be limited because of the physical capabilities of the thursters. I've estimated the authority for right now, but it should be changed later when the real command authority is found.

Currently, the way the controller is acting on the vessel is by simply applying a force in a given direction on the CoG of the vessel. For the surface vessel, any force given in Z-direction is ignored as the surface vessel will not be able to cancel its own heave in waves. There is no controller yet implemented for the ROV. In the current implementation, torque/yaw is also ignored, and the vessel has no controlled heading. In a future iteration, both the simplistic control and heading control could be implemented by splitting the force inputs from one single input at CoG to one input at the position of each thruster. Then yawing motion will also be applied with differential thrust and a yaw-term can be added to the controller.

Whether the complications mentioned in the previous paragraph are necessary is not clear yet. If we consider the ideal future implementation in a physical vessel, the controller designed now is only intended to give the total commands to the vessel. Thrust allocation and local control will be designed elsewhere and simply be a node in the ROS2 system that will be the final vessel. Either way, the option of making the simulation more true to life exists if it should be desirable.

Finally, the wire which connects the ROV and the surface vessel is created. AGX has two similar wire-like simulation objects: Wires and Cables. According to the documentation, because torsion of the wire is irrelevant, we want to be able to winch the wire in and out to simulate lifting and lowering the ROV and we are working on long wires, the Wire module should be used. The way wires work in AGX is as a series of links connected to or passed through a series of nodes. For this implementation only two nodes are necessary, one connecting the wire to the surface vessel and one connecting it to the ROV. The Wire module of AGX allows for winches to be simulated as well, with given speeds, gearings, torques etc.. I have not implemented this currently due to time constraints.

In addition to all the "necessary" elements, the simulation also has a manual controller for the vessels. It is possible to use the keyboard to give manual force inputs on the vessels. This uses the same framework for adding force as the controller does. I've done this as a way to debug and test the system a bit.

The final simulator can be seen on Github at `https://github.com/MagnusKjorseng/FordypOgMaster/tree/main/Simulator`

3.3 ROS2

ROS2, short for Robot Operating System 2, is an easily expandable and configurable operating system used primarily for hobbyists and research in control and robotics. The main selling point of ROS2 is its node model where different parts of a control system can be placed in separate, segregated nodes with certain interfaces. Those nodes then either publish data to or subscribe to data from what ROS2 calls topics. This system grants a developer or team of developers flexibility with regards to changing out certain nodes while still allowing the larger system to work. I.e. experimenting and changing out single nodes, so long as the same topics are still used, is extremely simple.

I was not able to implement ROS2 during this project. I believe this is because ROS2 is not designed to be used on Windows and requires a lot of workarounds which I was not able to figure out. This section is in the report more as a reference and a reminder for future iterations based on this report that ROS2 would make the project easily scalable and iterable.

AGX has the ability to work with ROS2, having built in methods for both publishing and subscribing to topics. Applied to this project it would in theory allow for the control system to be built in ROS2 and connected to the simulator. The control system could then be tested and tuned in different simulated environments until satisfactory results are achieved. When the control system works as intended, it can then be disconnected from the simulator and connected to a physical implementation of the simulated environment which would allow for real-world testing.

The end result of the process above would be two equivalent systems, one digital and one physical, which would allow for rapid prototyping in the digital space before quick deployment in physical space.

CHAPTER
FOUR

RESULTS

4.1 Simulation results

I have implemented a simulated surface vessel and a non-buoyant subsurface vessel, both of which are controllable either manually or by automated controller. The two vessels are bound together by a wire tether. The vessels and the wire are all affected by weather effects such as ocean currents, as well as physical effects like added mass and inertia.

The simulation works as would be intuitively expected. An example of the simulation graphical interface can be seen in fig. 4.1. The figure shows a surface vessel and the ROV under water in green, and the teal tether connecting them. The simulated water is shown as a grey volume, but it's not easy to distinguish it in fig. 4.1 because it takes up the entire screen.

4.2 Control system results

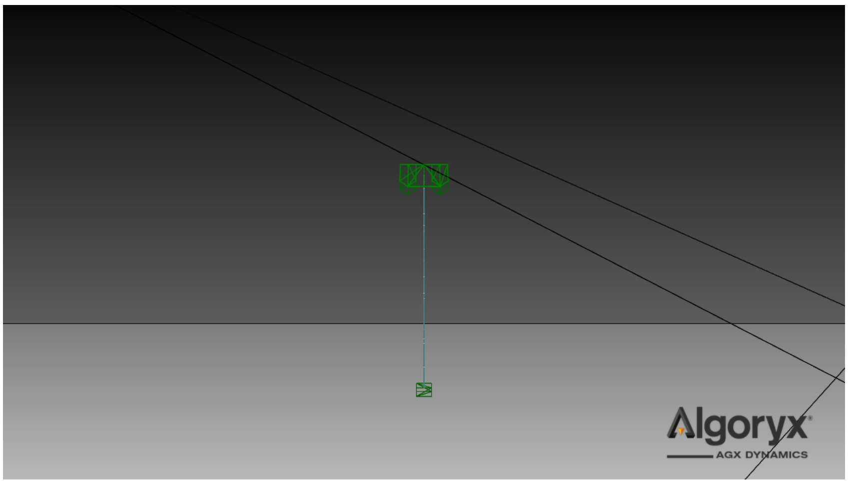

Figure 4.1: The graphical user interface of AGX with the simulation running

CHAPTER

FIVE

DISCUSSION

5.1 Use as a rapid prototyping tool

The solution shows a lot of promise as a rapid prototyping tool. As it stands at time of writing, the solution is fairly easy to configure for different initial conditions, depths of water/length of cable. Configuring the seastate is somewhat more complex as it's necessary to describe an elevation function for the sea surface. Sea currents also are not yet implemented, although AGX does allow for currents using the `WaterFlowGenerator` interface.

5.1.1 Ease of use

5.2 Future applicability

The goal of this project has been to make a simulation applicable to the Plan Sea project. I believe I have done this, even if it is a bit simplistic as it stands. I believe that the resulting simulation is applicable to the real-life system.

5.2.1 IRL testing proposal

For my Master's thesis, I would like to work further on this simulator to create a well functioning control system and then apply it to the real-life vessel and ROV.

CHAPTER

SIX

CONCLUSIONS

The goal of this project has been to make a simulation of the Plan Sea project's proposed implementation, which consists of a small surface vessel and a non-buoyant remotely operated vehicle attached to eachother by a lifting wire. The purpose of the simulation is to allow for rapid prototyping and tuning of a control system that allows for controlling the coupled system that results.

In this report I've documented why the simulation would be a helpful tool for prototyping, as well as how the simulation itself is set up. I've described how to use the simulation as it currently stands, its current state and results, as well as ways of expanding the simulation in the future to make it more realistic and applicable to the real world.

BIBLIOGRAPHY

[1] Jenna R. Jambeck et al. "Plastic waste inputs from land into the ocean". In: *Science* 347.6223 (Feb. 2015). Publisher: American Association for the Advancement of Science, pp. 768–771. DOI: 10.1126/science.1260352. URL: https://www.science.org/doi/10.1126/science.1260352 (visited on 06/12/2024).

[2] *Top 25 recycling facts and statistics for 2022*. en. June 2022. URL: https://www.weforum.org/stories/2022/06/recycling-global-statistics-facts-plastic-paper/ (visited on 06/12/2024).

[3] Atsuhiko Isobe and Shinsuke Iwasaki. "The fate of missing ocean plastics: Are they just a marine environmental problem?" In: *Science of The Total Environment* 825 (June 2022), p. 153935. ISSN: 0048-9697. DOI: 10.1016/j.scitotenv.2022.153935. URL: https://www.sciencedirect.com/science/article/pii/S0048969722010270 (visited on 06/12/2024).

[4] Ibukun Oluwoye et al. "Degradation and lifetime prediction of plastics in subsea and offshore infrastructures". In: *Science of The Total Environment* 904 (Dec. 2023), p. 166719. ISSN: 0048-9697. DOI: 10.1016/j.scitotenv.2023.166719. URL: https://www.sciencedirect.com/science/article/pii/S0048969723053445 (visited on 06/12/2024).

[5] Walter Lian and Bjem Sortland. "Manoeuvering of Bodies Suspended at Extreme Water Depth". en. In: Los Angeles, May 1996. (Visited on 10/12/2024).

[6] Peng Chen et al. "Dynamic characteristics of deep-sea ROV umbilical cables under complex sea conditions". In: *Ocean Engineering* 239 (Nov. 2021), p. 109854. ISSN: 0029-8018. DOI: 10.1016/j.oceaneng.2021.109854. URL: https://www.sciencedirect.com/science/article/pii/S002980182101204X (visited on 19/09/2024).

[7] Thomas Thuesen Enevoldsen et al. "Simplified Modelling and Identification of an Inspection ROV". en. In: *IFAC-PapersOnLine* 51.8 (2018), pp. 257–262. ISSN: 24058963. DOI: 10.1016/j.ifacol.2018.06.386. URL: https://linkinghub.elsevier.com/retrieve/pii/S240589631830716X (visited on 19/09/2024).

[8] Enrico Anderlini, Gordon G. Parker and Giles Thomas. "Control of a ROV carrying an object". en. In: *Ocean Engineering* 165 (Oct. 2018), pp. 307–318. ISSN: 00298018. DOI: 10.1016/j.oceaneng.2018.07.022. URL: https://linkinghub.elsevier.com/retrieve/pii/S0029801818312654 (visited on 19/09/2024).

[9] Per J. Thingstad and Haakon D. Hveding. “A Nonbuoyant ROV for Performing Heavy Subsea Work”. en. In: *Offshore Technology Conference*. Houston, Texas: Offshore Technology Conference, 1982. DOI: 10.4043/4182-MS. URL: http://www.onepetro.org/doi/10.4043/4182-MS (visited on 19/09/2024).