Candela AutoDocking

An autonomous docking system for Candela Speedboat

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Abstract

Candela is an innovative boat company based out of Stockholm that produces all-electric, hydrofoil speed boats. They have recently started exploring solutions for public transportation and autonomous navigation and their first vessel to utilize such technology is the "P-30"; a ship that will replace the current fleet of diesel SL commuter ferries in Stockholm. The goal of this project is to explore autonomous solutions specifically for the docking sequence of the P-30. As such, the scope involves designing, fabricating, and testing a prototype P-30 to analyse how well the conceived methodology achieves autonomous docking in the same circumstances as the current SL ferries.

This report includes a study of current state of the art solutions for autonomous navigation, a study of associated technologies for the boat prototype, a proposed solution for the project task, and an outline of future plans for further project development. The proposed solution includes the embedded use of GNSS, stereo vision cameras, and ultrasonic sensors to localize and control two trolling motors that maneuver a small Jon boat. Fabrication of this prototype will start in September of 2021 and integrated system testing will begin in late October, 2021.

Acknowledgements

We would like to thank Candela and Bruno Bosco for providing us with such a fascinating project and offering their continuous feedback and support. We also would like to thank our project coach, José Manuel Gaspar Sánchez, for his guidance and insightful advice toward the project approach and course deliverables. Similarly, thank you to the rest of the supervising staff who have given us further advice and critique that has improved our project considerably.

AutoDocking Team,
Stockholm, May 2021

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Acronyms

AAWA Advanced Autonomous Waterborne Applications. 16

AGM Absorbent Glass Mat. 21, 57, 61, 65

AHRS Attitude Heading Reference System. 13

ANS Autonomous Navigation System. 17

ASV Autonomous Surface Vehicle. 14, 15, 37

AUV Autonomous Underwater Vehicle. 14, 15

BLDC Brushless DC Motor. 28

BMS Battery Management System. 25

BOM Bill of Materials. 67

CNN Convolutional Neural Network. 45–47

DGNSS Differential Global Navigation Satellite System. 34

DOF Degrees of Freedom. 31–33

EKF Extended Kalman Filter. 14, 39

EPS Electrical Power Steering. 27

FMCW Frequency-Modulated Continuous Wave. 43

FOV Field of View. 41, 42, 62

GLONASS Global'naya Navigatsionnaya Sputnikovaya Sistema. 33

GNSS Global Navigation Satellite System. 12, 33, 34, 38, 59

GPS Global Positioning System. 13, 15, 33, 57

IMU Inertial Measurement Unit. 14, 15, 35, 57

KF Kalman Filter. 38, 39, 57

KV Constant Velocity, No-load speed at 1 volt. 19

LiDAR Light Detection and Ranging. 12, 13, 15, 17, 40, 41, 61, 62

LiFePO4 Lithium Iron Phosphate. 21, 23–26

LQR Linear-Quadratic Regulator. 16, 37

M2M Machine-to-Machine. 59

MPC Model Predictive Control. 16, 38

NED North-East-Down. 31, 32

NTRIP Networked Transport of RTCM via Internet Protocol. 34, 60

PID Proportional–Integral–Derivative. 16, 37

PLM Product Lifecycle Management. 4

RTCM Radio Technical Commission for Maritime Services. 34

RTK Real-Time Kinematics. 12, 34, 59

SMC Sliding Mode Control. 16, 37

SoTA State of the Art. 3, 10, 21

TOF Time-of-Flight. 40, 48

VRLA Valve Regulated Lead-Acid. 21

Chapter 1

Introduction

This chapter describes the background, scope, requirements and team structure for the project.

1.1 Background

Climate change is the most existential issues of our time. The automotive industry has been heavily criticized and increasingly regulated for their part in this issue, but marine transportation is often overlooked despite the fact that traditional 7.5 m petrol boats consume roughly 15x more fuel than a family car. Candela, an innovative boating company based in Stockholm, is making strides to correct this issue by providing a zero-emission alternative. Not only are their boats greener, they are also more efficient, save owners money, and provide increased performance and comfort compared to their petrol alternatives.

Candela designs and manufactures 100% electric, hydrofoiling boats [65]. Their first and only current boat model is the C7, see Figure1.1; a speed boat that utilizes an actively controlled hydrofoiling system to lift its carbon fiber hull above the waves when speeds reach 17 knots. This reduction in drag means the electric motors of the boat can operate significantly more efficiently, resulting in a range comparable to conventional petrol boats. To keep the vessel stable during "flight", an array of sensors such as IMU, GPS, and ultrasonics gather data that is processed and utilized to control hydraulic actuators at a rate of 100 Hz.

Figure 1.1. Candela C7 speed boat [65].

The success of the C7 has allowed Candela to grow and turn their sights to more ambitious endeavours... such as revolutionizing the public transportation sector. Their first venture into this new market is the P-30, see Figure 1.2. This new vessel will utilize the same electric and hydrofoiling technology of the C7, but scale it up with dual independently controlled motors that can transport 30 commuters. This ship is intended to replace the current fleet of diesel SL ferries in the Stockholm area and it is already in early development. With a speed of 30 knots and zero wake, it will be the world's fastest electric passenger ship and reduce commute times by 50%. Not only will it be fast, it's cutting-edge technology will also cut operational costs in half and provide passengers a smoother ride.

Figure 1.2. Candela P-30 concept rendering [65].

In parallel to developing the P-30, Candela is also exploring various means of autonomous navigation that can be integrated into their new vessels. This added functionality will increase safety in the long term, lower operational costs even further, and improve the consistency of the route scheduling when applied to commuter ships such as the P-30. This project is part of this endeavour by exploring viable solutions for autonomously docking the P-30 specifically. A scaled down prototype of the P-30 will be designed, fabricated, and then used for testing a methodology toward autonomous docking.

The main purpose of this report is to convey the research done toward various State of the Art (SoTA) solutions for autonomous docking, navigation and other associated vehicles that pertain to the project task. It also describes the necessary research done for designing the prototype vessel. In addition to said research, this report also discusses project requirements, the generated concepts, evaluation of said concepts and the final design that was ultimately chosen. The last portion of the report describes the future plans for the project moving forward.

1.2 Scope

To better illustrate how the project scope developed during the initial problem identification phases of the project, this section is broken down into two subsections; *Initial Scope* and *Refined Scope*. The *Initial Scope* refers to the desired scope initially pitched by stakeholders and the *Refined Scope* is the more simplified and focused version that ultimately guided project tasks.

1.2.1 Initial Scope

The initial scope presented by stakeholders was broad in that the overall desire was to automate everything the current SL ferry does while docking and in a similar environment. In the initial pitch presented by stakeholders, the desire for the following AutoDocking prototype “key features” were shown...

- ”Sensing depth and determining if docking is possible.”
- ”Automatically align with and approach the dock.”
- ”Avoiding collision with dock or other obstacles.”
- ”When in position, automatically deploy a gangway to allow passengers to leave or enter the ferry.”
- ”Holding the docking position until gangway is retracted, and operator gives the signal to leave the dock.”

This list encapsulated everything the real P-30 would be required to do, but it was also stated that ”The project can be taken on in part or as a whole depending on the outcome of the pre-study and consequent time plan”... The *Refined Scope* delves into how how these desired features were refined and made more feasible.

1.2.2 Refined Scope

After several meetings with the stakeholders and internal team meetings, the scope was better understood and areas of greater/less importance were identified. A more feasible and focused project scope was generated and is summarized by the points below.

- No gangway will be included in the project.
- The prototype's hull will be purchased to increase feasibility and does not need to mirror the P-30 (no hydrofoils and specific shape doesn't matter).
- There will be dual, independently controlled outboard motors placed at the stern of the boat for portability to the P-30.
- The dock will mirror those used by current SL ferries and require minimal modifications.
- When viable, a communication protocol similar to the P-30 will be used.
- Some basic obstacle detection and avoidance will be implemented, but advanced avoidance protocols and detection (such as those needing the training of large data sets) will not be required.
- The prototype will operate well in calm environmental conditions and attempts will be made to make it more robust if more time is available later on.
- The prototype will be designed to operate well during normal visibility and daylight conditions and efforts will be made to improve on this only if time allows.

In general, the stakeholders did not want to impose many hard requirements and instead wanted autonomous docking methodologies freely explored. Many of the items listed were therefore conceived by the team to increase feasibility and establish requirements.

1.3 Requirements

To better solve the overall task, the scope was broken down into a list of requirements that the project had to satisfy in order to be considered successful. Input was gathered from the stakeholders (*Stakeholder Requirements*) regarding desired system function and then further detailed and quantified (*Technical Requirements*) so test cases could be built upon them. Polarion , a Product Lifecycle Management (PLM) software develop by Seimens, was used to create requirements and link specific stakeholder/technical requirements to one another [27].

1.3.1 Stakeholder Requirements

The following system requirements were those identified by the stakeholder. Candela was hesitant to place many hard requirements on the project (as not to stifle innovation), so many were also identified by the team to help guide the project. Those that are labeled *extra scope* are requirements that were initially requested by Candela, but not required to consider the project a success. These requirements will be fulfilled if the group has time and resources remaining when the fixed requirements are fulfilled.

The following list describes the stakeholder requirements. They are categorized into five types... *Project Admininstration, System Portability, Autonomous Protocol, Obstacle Detection and Avoidance,* and *System Robustness.*

- Project Administration
  - **Purchasing:** Purchase requests shall be reviewed by the stakeholder prior to placement.
- System Portability
  - **Dual Outboard Motors:** The vessel shall have dual, outboard electric motors that are controlled independently.
  - **Dock Design:** The layout of the dock shall mimic those used by the SL ferry system in Stockholm.
  - **Communication Protocol:** The prototype's embedded system architecture shall utilize the same communication protocol as the P-30 concept.
- Autonomous Protocol
  - **Autonomous Navigation:** The prototype vessel shall reliably align and approach the dock fully autonomously without the need of operator intervention.
  - **Docking Time:** The time it takes to successfully dock shall be comparable to that of the current SL ferry system.
  - **Dock Departure Protocol:** The vessel shall hold its position at the dock until signaled to leave by the operator.
  - **Abort Signal:** At any point in time, a driver shall be able to stop all operations by means of some signal.
- Obstacle Detection and Avoidance
  - **Environmental Obstacles:** The vessel should be able to detect various obstacles and avoid them accordingly.

  - **Depth Sensing (Extra Scope):** The vessel should be able to detect the water depth and quickly abort the navigational path if depth is too shallow.

- System Robustness
  - **Lighting Conditions:** All vessel sensors shall be robust against various lighting conditions similar to those experienced during normal SL ferry operation.
  - **Drivetrain Environmental Robustness (Extra Scope):** Motor control system should be robust against localization errors induced by various environmental disturbances (i.e. wind, wakes, current, etc.).
  - **Sensor Environmental Robustness (Extra Scope)** The on-board sensors should be robust against various environmental conditions that the SL ferries regularly encounter.

1.3.2 Technical requirements

To better quantify and detail specifics for the respective stakeholder requirements, a list of technical requirements were created. These are reflected in the list below and categorized in the same methodology as the stakeholder requirements...

- Project Administration
  - **Budgetary Approval:** Project budget shall be 50,000 kr (not including tax), but variable at the discretion of stakeholders depending on how purchases are deemed as value added.
- System Portability
  - **Dock Form Factor:** The docks used for testing shall be a rigid flat wall, without anything guiding the vessel, and detectable at varying heights.
  - **Dock Material:** The docks contact surface shall be covered in a layer or rubber or other high friction material similar to those used in the various SL ferry dock locations.
  - **Dock Modification:** No excessive modifications to pre-existing SL ferry docks should be required to successfully detect it or hold the position of the vessel.
  - **Motor Rotation Range:** The dual motors shall each have a minimum range of movement of +/- 30 degrees.
  - **CAN Bus Protocol:** A CAN communication protocol shall be used in the case of multiple processors and as long its viable for the particular sensor/purpose in question.
- Autonomous Protocol

- **Navigational Control in Nominal Conditions:** The navigational control system shall operate with minimal error during nominal environmental conditions (no waves/wakes, no current, and low wind speed).
- **Dock Impact Speed:** The prototype vessel shall not impact the dock at more than 0.03 m/s velocity (or $< 0.6\ m/s^2$ deceleration).
- **System Range:** The vessel shall be able to identify the dock and make necessary path adjustments from a radial distance of 50 m.
- **Dock Accuracy:** The boat shall make contact to the dock within a +/- 0.5 m accuracy of true position.
- **Docked Angular Movement:** The boat shall not wander further than +/- 5 degrees from the predefined angle.
- **Dock Slipping:** There shall be no slipping from the contact point between the dock and vessel.
- **Docking Time Allowed:** The vessel shall not take longer than 1 minute to successfully dock from its initial starting point.
- **Departure Heading Correction:** While leaving the dock, the boat shall reverse from the dock at the same predefined angle as docking for 10 m before correcting its heading to depart further.
- **Manual Abort Timing:** When an abort signal is sent, the vessel shall begin abort sequence no longer than .1 s from when signal is sent.
- **Navigational Control in Poor Environmental Conditions (Extra Scope):** The control system of the vessel should be robust against errors induced by extreme environmental conditions (large waves/wakes, current, high wind speed, etc.).

- Obstacle Detection and Avoidance
  - **General Abort Detection:** If a large object is detected in the way of the docking path, then the boat shall stop and wait until re-initialized by the operator.
  - **Depth Induced Navigational Abort (Extra Scope):** The boat should abort its autonomous docking sequence if detected water depth is less than 0.7 m.
  - **Avoid Other Boats (Extra Scope):** The vessel should be able to detect other boats in the water and avoid them accordingly.
  - **Detect Swimmers (Extra Scope):** The vessel should be able to detect people swimming in the water and avoid accordingly.
- System Robustness
  - **Lighting Condition Robustness:** The vessel's sensors shall be operational during various daytime lighting conditions.

- **Lighting Recognition:** The system shall be able to detect if the lighting condition is insufficient for proper operation and notify the operator.
- **Additional Lighting Conditions (Extra Scope)** On-board sensors should be robust against all lighting conditions, including nighttime and artificial lighting.
- **Sensor Environmental Robustness (Extra Scope)** The on-board sensors should be robust against weather conditions regularly seen by Stockholm's ferry system, such as heavy rain, fog, snow, etc.

1.4 Team Structure

To more efficiently research and develop specific aspects of the project, the team was divided into four different subsystems...*Drivetrain, Control and Position, Obstacle Detection, and Near Field.* These were identified during an initial brainstorming session where pre-conceived knowledge and approaches were discussed (Figure 1.3).

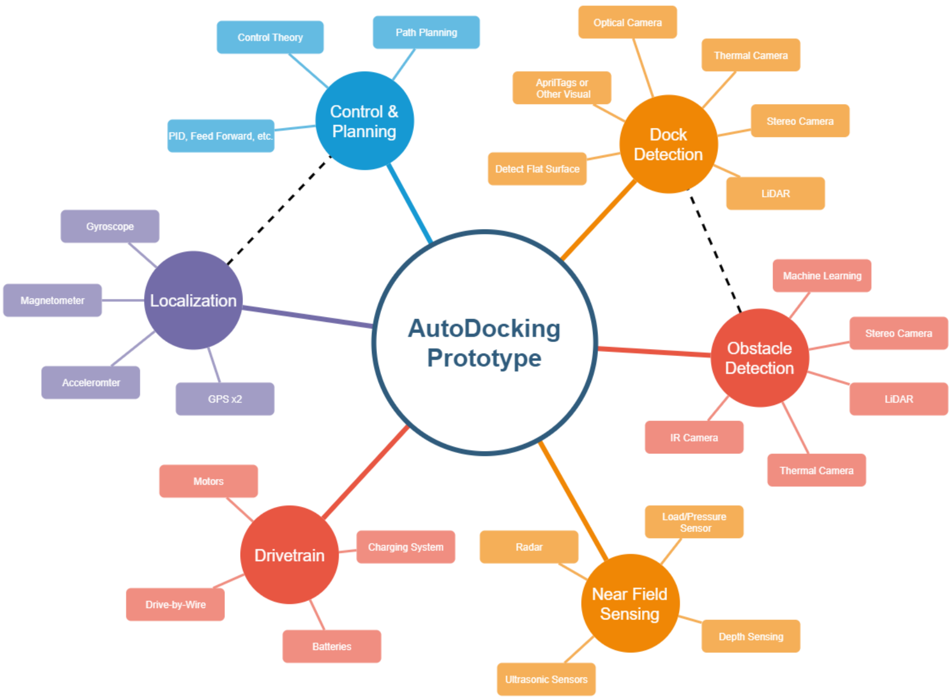

Figure 1.3. Mind map used to develop team structure.

They were divided based on system dependencies, functionality, and associated hardware. By doing this, subsystems could be researched, designed, fabricated, and tested by the same members prior to integrating into the entire system. Figure 1.3 show how "Control & Planning" was combined with "Localiztion" to form the *Con-*

trol and Position subsystem and how ”Dock Detection” and ”Obstacle Detection” was combined to form just *Obstacle Detection*.

Chapter 2

State of the art

This chapter describes the SoTA, featuring earlier research and implementation of fully or partially autonomous marine vessels and other vehicles. Furthermore, it presents theory and hardware needed in order to model, control, position and drive a marine craft for the scope of this project. Lastly, the chapter presents existing hardware and strategies in order to detect objects, obstacles and hazards in different ranges.

2.1 Earlier similar work - Marine Vessels

2.1.1 Wärtsilä SmartDock

In 2018 the Finnish company Wärtsilä succefully tested a fully automated ferry docking system. The test was done on the Norweigan Ferry Folgefonn which successfully docked in the harbour of Stord. Today they are delivering this as a commercial solution [89] [88]. The SmartDock system as they call it, is a part of Wärtsiläs SmartMove Suite. It provides sensors for accurately determining the Wind Speed, Pitch, Roll, Heading, Position and Ship Model. With this information from the sensors the system can safely and autonomously dock the ferry from a range of 2000 meters [90]. The sensor used to create an accurate position of the vessel when docking is the CyScan. CyScan is a Dynamic Position laser sensor and is able to detect and locate prisms stationed at the dock, see Figure 2.1. With the information about the relative position to the prisms the vessel can accurately determine its location and from there on proceed to dock [50].

Figure 2.1. The prism located at the dock side [51].

2.1.2 Hammerhead Vision System

The United States Navy has along with the Jet Propulsion Laboratory developed an autonomous suite for unmanned surface vessels. Two key components of the system are the hammerhead system and the R4SA. The hammerhead system is a vision-based system for detection and tracking of static and dynamic objects from a high-speed vehicle. The R4SA is a framework for implementing navigation behaviour such as obstacle detection and target following. The hammerhead system consists of four cameras that are arranged in a left-facing pair and a right-facing pair to gain a very wide field of view [26]. The images captured by the stereo cameras are used to create a local hazard map and a list of contacts which is then transmitted to the R4SA system. The R4SA system then uses the given data for hazard avoidance and for the tracking behaviour [26]. An example of how the hazard map can look like can be seen in Figure 2.2.

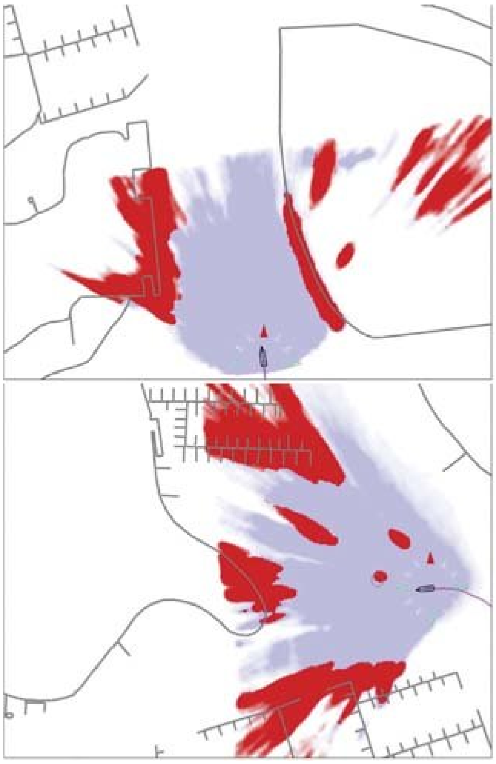

Figure 2.2. Red shows areas with high hazard probabilities and blue indicates where there is coverage by the hammerhead system [26].

2.1.3 Yanmar

Yanmar is multinational company which originates from Japan. They provide engines for a great variety of applications such as agriculture, construction and marine [96]. The company also went in to the autonomous boat business in 2017. Yanmar has since then had great success in their concept testing. Their proof of concept vessel uses a twin-propeller, twin-rudder ship combined with a thruster for increased maneuverability (Figure 2.3). When it comes to the autonomous part of the concept, Yanmars first iteration utilized Real-Time Kinematics (RTK). This gave the boat great positioning accuracy, but the vessel could only dock at ports fitted with RTK stations. To further develop this, the company moved over to a system where they combined LiDAR technology with Global Navigation Satellite System (GNSS). This new combination allowed the boat to autonomously dock at ports even if they where not fitted with an RTK station [97].

Figure 2.3. Yanmars concept vessel with a LiDAR unit in the front [97].

2.1.4 Raymarine Assisted Docking

Raymarine is a company that specializes in high performance marine electronics for the recreational boating market and light commercial marine industry. Their aim is to deliver the best intelligent navigation systems and sensors for safer marine operation. The Raymarine DockSense™ Control is an object recognition and motion sensing assisted docking solution. The solution utilizes intelligent FLIR machine vision camera technology (3D Stereovision) to analyze real-world imagery to create a 3D-map and effectively generate a virtual bumper around the boat, as seen in Figure 2.4. The vision system is integrated with the vessel's propulsion and steering system to help the driver with docking maneuvering, making it partially autonomous. It also uses Global Positioning System (GPS) and an Attitude Heading Reference System (AHRS) to compensate for wind and currents. [67].

Figure 2.4. Raymarine vision system that creates a virtual bumper around the boat [66].

2.1.5 Autonomous Docking Research

In 2007, Martins et al. [52] presented a paper where they performed the docking of an Autonomous Surface Vehicle (ASV) with an Autonomous Underwater Vehicle (AUV) based in visual information. A hybrid systems approach is used in the docking manoeuvre synthesis, as displayed in Figure 2.5, and the control law is represented by a hybrid automaton with both discrete and continuous states. To determine the relative position and attitude between the two vehicles, the visual information was fused with Inertial Measurement Unit (IMU) measurements in an Extended Kalman Filter (EKF).

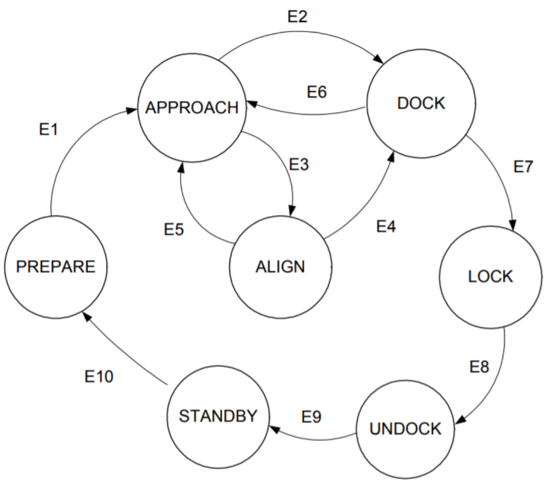

Figure 2.5. Discrete states of the hybrid manoeuvre used by Martins et al. [52].

A hybrid systems docking approach was also used by Braga in 2010 where he developed a control strategy for an AUV to dock into a mounted underwater docking station [10] and by Rosa in 2017 where he developed autonomous docking between an AUV and ASV based on GPS and IMU data [73].

In the work from 2019, Leite developed a self-guided docking architecture for ASVs [40]. The architecture incorporates data readings from GPS, LiDAR, camera and IMU and is presented in Figure 2.6. The docking operation first begin when correct position and orientation requirements are met. To fulfill these conditions, the Catch-Zone Approach and Reorientation Module are used. When the requirements are met, the Docking Approach may be initiated, which is the module conducting the approach towards the dock. The Supervisory Control System in the architecture is used to supervise and monitor the docking manoeuvre.

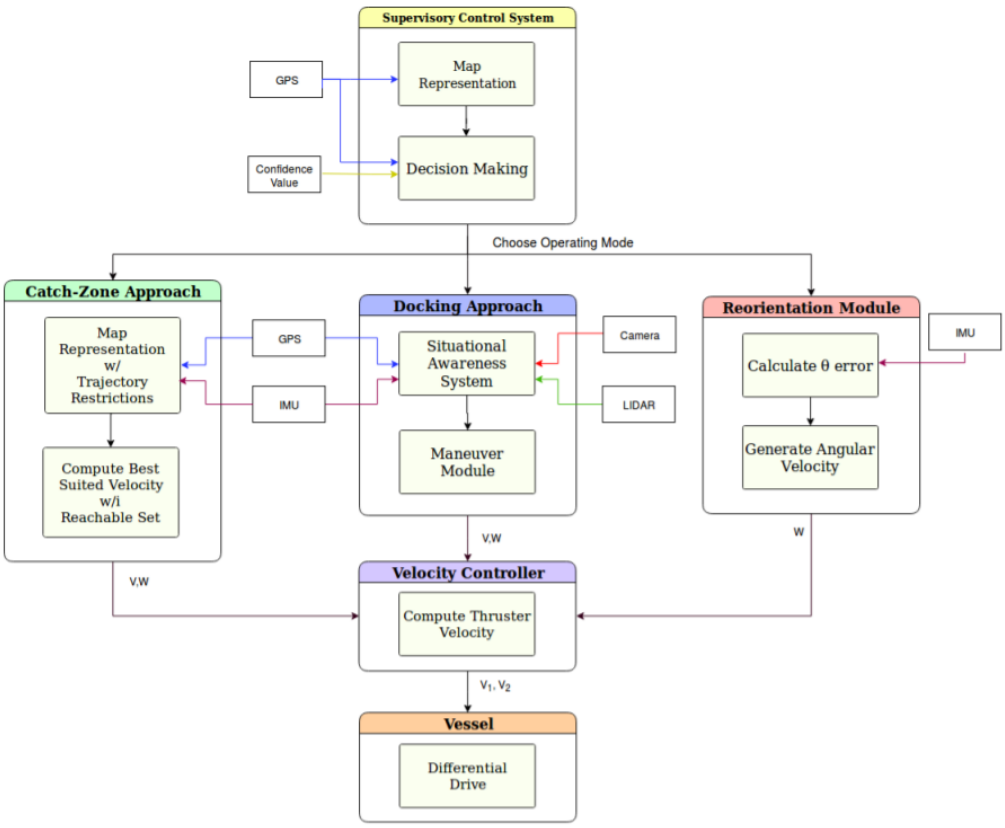

Figure 2.6. Overview of the self-guided docking architecture developed by Leite [40]

On the topic of control and guiding the vessel towards the dock, plenty of papers exist. In 2019, Wang et al. presented a comprehensive article on the matter [87]. As stated, common algorithms for motion control are Proportional–Integral–Derivative (PID) control, optimal control with e.g. Linear-Quadratic Regulator (LQR), Sliding Mode Control (SMC) and Model Predictive Control (MPC). The relationship between all algorithms discussed in the article is displayed in Figure 2.7. Also stated is that the research on the autonomous docking of ships is not very extensively presented in the article, though the main control algorithms found to be used for this purpose are mainly PID and/or neural network based.

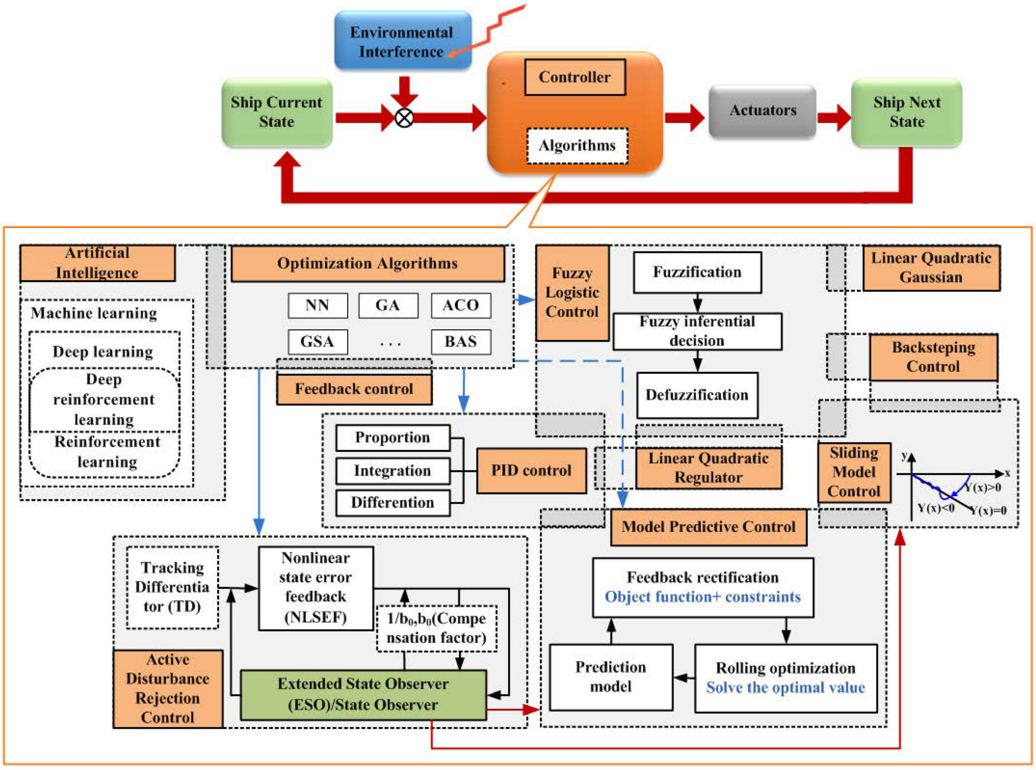

Figure 2.7. Relationship of motion control algorithms as stated by Wang et al. [87].

2.1.6 AAWA Initiative

The Advanced Autonomous Waterborne Applications (AAWA) Initiative is a large and well-funded project co-operation between institutes and maritime companies. The aim is to produce specifications and designs for the next generation of advanced ship solutions [71]. They emphasize the importance of sensor fusion to provide reliable and sufficient performance for situational awareness in all conditions for autonomous vehicles. The fused sensor data should seamlessly be integrated with path planning and reactive collision avoidance systems and their proposed architecture for this module integration can be seen in Figure 2.8. For situational awareness, their research suggests that short range radar or LiDAR can provide accurate range, velocity and angular measurements of objects, while cameras provide better spatial resolution to classify objects. Near-IR cameras or thermal cameras could also be used for night-time imaging but may be prone to failure under difficult weather conditions, where radar would be a better performer [71].

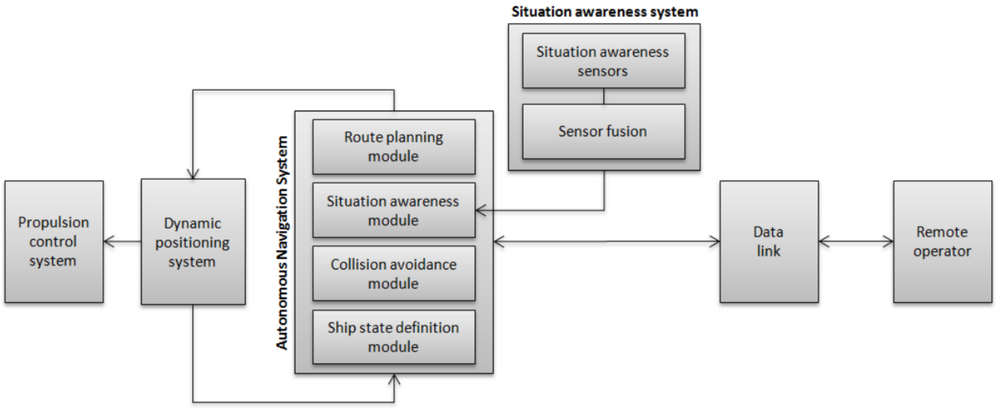

Figure 2.8. ANS architecture [71].

2.2 Earlier similar work - Other Autonomous Vehicles

Autonomous driving is not only a hot topic among boats. The car industry has been aiming for self driving cars for a long time, and for example, self parking is a common feature in new cars. Even though cars and boats are very different, there are lots of similarities in detecting the surrounding required for autonomous driving.

2.2.1 Tesla

Tesla is a new thinking and innovative car company. It might also be the car company with most progress into the field of autonomous driving. They all ready have a number of driving assisting and safety features such as autopark, autosteer and emergency breaking. All Tesla's cars are sold with the hardware for full autonomous driving. This makes it possible to offer full autonomous driving in the future to customers buying a car today, just by updating software [6]. The hardware implemented by Tesla to make autonomous driving possible consists of a number of cameras, distance sensors and radar as seen in Figure 2.9. There are eight cameras providing 360 degree vision around the car as well as twelve ultrasonic sensors around the car to detect cars or other objects while driving and parking. At last there is a robust radar detecting forward objects. By this setup, Tesla expects their cars to be able to fully autonomously and safely drive the fastest route between two different places.

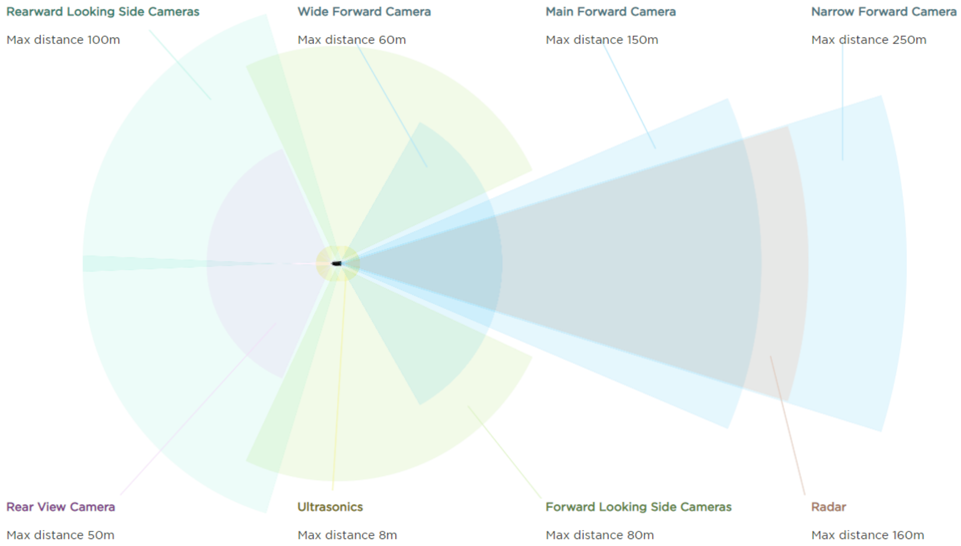

Figure 2.9. Tesla's setup of sensors in order to assist the diver, and possibly provide self driving in the future [6].

2.3 Drivetrain

The drivetrain subsystem of the project includes the various hardware components needed to make a scaled model of the P30 and propel it. Boat hull, outboard motors, actuation and power supply all fall into this category.

2.3.1 Outboard Motors

There are several ways to drive a boat forward; outboard/inboard motors, bow mounted, thrusters etc. In order to make the project as portable to Candela's P30 as possible, only stern mounted, electric outboard motors have been researched.

Further limitations by the portability to the P30 include:

- Dual motors.
- Electric to control thrust via voltage signal.
- Individually controlled to allow vector steering ($\pm 30°$).

In an electric motor the throttle is controlled only with a voltage signal from an on board computer. Since the P30 is also electric, having as similar motors as possible ensures better portability to the real system. There are different options for electric motors depending on the scale of the system relative to the P30. Options are RC motors for model boats, small electric trolling motors or full size outboard motors. Important to note is that as the motors and scale of the project gets bigger, the price of components increase exponentially. However the project scale is ultimately a decision concerning a lot of different factors, not only the motors.

RC motors

There are plenty of powerful RC motors on the market. An RC boat can be driven at very fast speeds compared to its size, since the drag of the water becomes close to zero and because the motor doesn't need a lot of torque, only a very high RPM. An example is the Volantex V792 RC speed boat, which has a potential top speed of 33 knots using an 1800kv (Constant Velocity, No-load speed at 1 volt (KV)) brushless DC motor. However there are still problems with with a small RC boat design that makes it hard to follow the limitations of the project. Generally, a DC motor is usually fit in the middle of the boat, with a rigid axis going through the whole boat to the propeller. There are examples of RC outboard motors that fit the scope of the project, however these are hard to find, very expensive and not nearly as powerful as their rigid shaft counterparts. Both the regular onboard motors and outboard motors are shown in figure 2.10. It is difficult to fit two of these motors along with a drive-by-wire solution that allows both motors to be individually rotated on such a small scale.

Figure 2.10. Onboard and Outboard RC motors [63].

Electric Trolling Motors

There are also many viable motors on the market for scale models larger than RC boats. One example is small electric trolling motors, shown in figure 2.11. These are mainly used for fishing, attached to smaller boats such as jon boats, kayaks and row boats. They come in a variety of different models and amounts of thrust, ranging from 133N up to 490N. These motors are fit to the back of a smaller vessel, and are controlled by an operator rotating them in any direction. Because they are big enough to fit the driving DC motor in the water with the propeller, the operator can rotate the motor 360 degrees without the need of a rudder. The thrust is controlled by rotating the handle connected to a potentiometer adjusting the voltage to the motor. The maximum speed of these motors is not very high, a single trolling motor with a forward thrust of 245N is capable of propelling a three meter long jon boat at roughly five kph [31]. 245N is the max thrust available for one 12V motor, higher thrust systems require 24V, which in turn doubles the amount of batteries needed.

Figure 2.11. Example of a small electric trolling motor [57].

Custom built motors

Due to the simplicity of an electric boat motor, one could realistically be built to be tailored to the scope of the project. An electric boat motor is essentially a brushed DC motor with a propeller attached. In order to control the speed, a potentiometer is used to modify the voltage going to the motor, and to control direction, the whole motor is rotated around its y-axis.

The advantages of designing and building a custom boat motor are mainly cost and customization. By buying parts it is possible to meet all requirements set by the project scope, from thrust to choice of control system to size and form factor of the motor 2.12. Cost is reduced due to reduced price of individual parts, cost of labour is removed, as well as a lot of parts that come with a commercial motor is not necessary. However there are also problems with building a custom motor. Even though the circuitry is not a problem to design, since it is under water the enclosure needs to be very high tolerance and precisely made to ensure no leakage. To make a motor at such high standards is time consuming since ensuring good performance needs extensive testing.

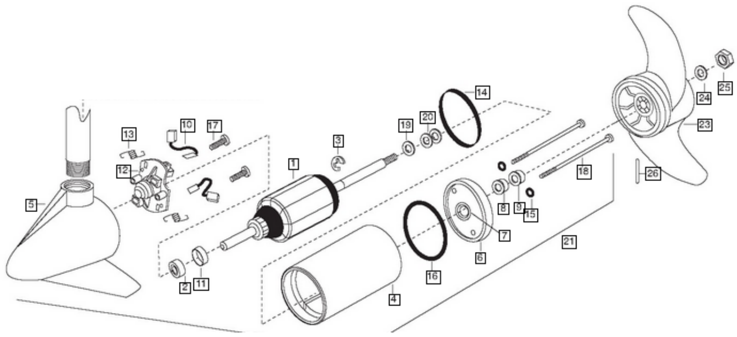

Figure 2.12. Parts diagram of an electric trolling motor [56].

2.3.2 Accumulator

The "accumulator" refers to the main power source of the vessel, or more specifically, the system of rechargeable batteries with the absence of a generator. Since the boat will be far from shore while testing, it must have its own power supply. There is a plethora of battery types and the technology is constantly changing. For that reason, this particular SoTA discussion will focus specifically on batteries that are commonly used in pertinent applications, such as marine and electronic hobbyist applications. Such battery types include Absorbent Glass Mat (AGM), LiFePO4, and custom lithium cell battery packs.

AGM Deep Cycle Batteries

AGM batteries have a similar construction to the average lead-acid battery commonly found in everyday cars. With these batteries, a series of lead-alloy plates act as electrodes and are suspended in an electrolyte (sulfuric acid most commonly). While discharging, electrical current is produced because negatively charged ions in the sulfate flow from the positive (cathode) terminal of the battery to the negative (anode) terminal [3].

AGM batteries work in this same manner, but rather than being flooded with liquid acid, a fine mesh of glass fiber absorbs the fluid and the excess is removed (see Figure 2.13). They are also classified as a Valve Regulated Lead-Acid (VRLA) batteries because they are fully sealed [86]. This makes them much safer since acid can't leak out and are less prone to vibration induced damage. AGM batteries are commonly found in aerospace, racing, and boating applications for that reason.

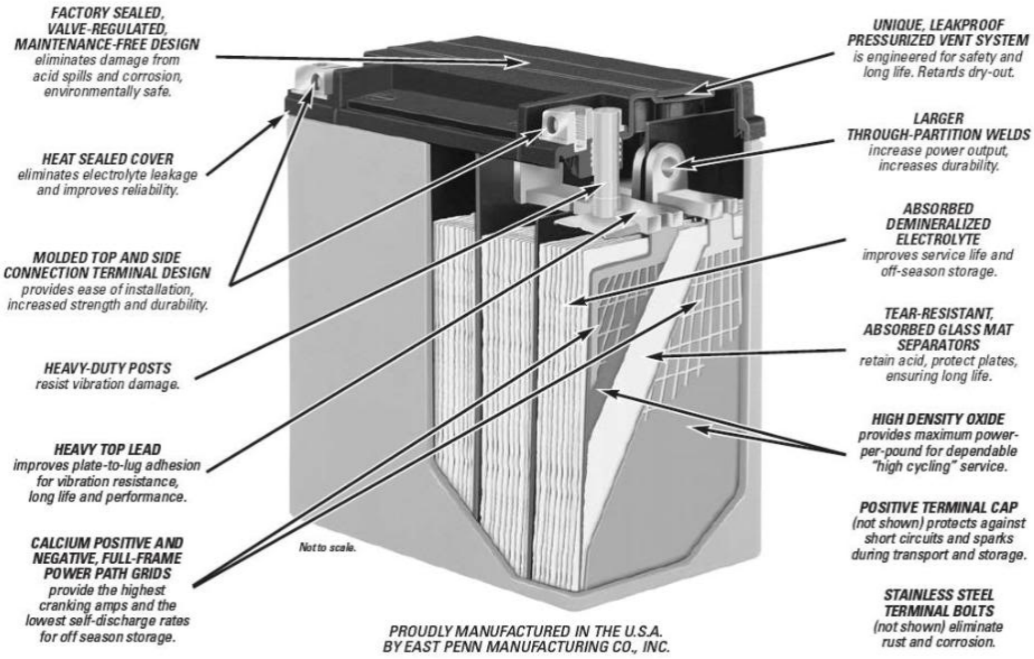

Figure 2.13. AGM battery construction [48].

One major negative of sharing the same construction as normal lead-acid batteries is their weight. Unlike modern lithium batteries, AGM batteries still consist of heavy lead plates and fluid (even if they are contained in fiber mats) which makes them very dense. This means that AGM battries have a very low energy density (Wh/kg, capacity per kg) and most weigh between 30-45 kg. This same construction also makes them more sensitive to cold weather in comparison to more modern battery types.

Like other lead-acid batteries, their low internal resistance does mean that they have a high power density though; making them perfect for applications that require large amounts of current to be drawn instantaneously. This is another reason why they are commonly used in cars...the electric starter motor quickly draws large amounts of current and these are up for that task. This also makes them a perfect candidate for powering larger DC motors, such as trolling motors.

More importantly, they are also considered a *deep cycle* battery. This means that unlike conventional lead-acid batteries, AGM batteries have a relatively long life cycle thanks to their glass matting and sealed structure. An AGM battery can withstand roughly 500-1300 discharge cycles depending on the depth of discharge (how much of the capacity is depleted). The two parameters are closely correlated and is represented in Figure 2.14. With that being said, these batteries do not have a constant discharge rate. Once an AGM battery is discharged to roughly 50% capacity, voltage drops drastically. A good charger is also important in the case of cycled use since they are sensitive to overcharging. This can damage the batteries and lower capacity permanently just as much as excessive discharging.

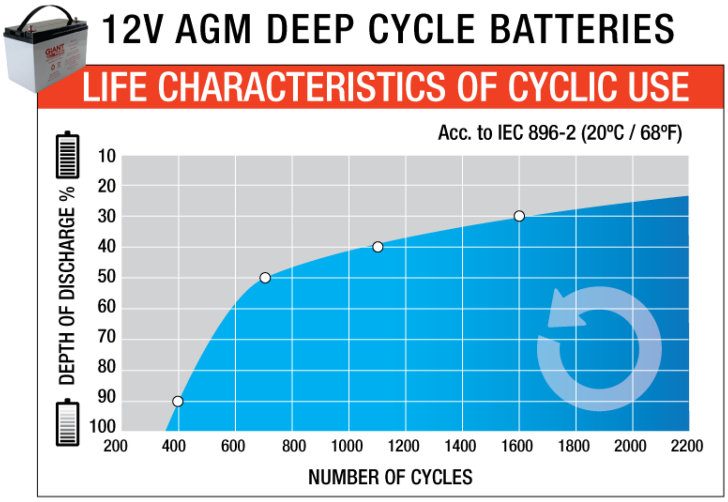

Figure 2.14. AGM battery lifecycle as a function of discharge depth [3].

Since AGM batteries are commonly used in the automotive industry, they are easily found in 12V form factors and are readily available up to 100 Ah capacities. In addition, this technology is well established and inexpensive to manufacture, so they are much cheaper compared to more modern lithium battery architectures (1200 - 2400 kr).

LiFePo4 Battery

In recent years, lithium battery types have been increasingly used in a multitude of different applications. Specifically, LiFePO4 batteries are commonly sold in 12V configurations and are used as an upgrade in applications where AGM batteries are common (aerospace, automotive, marine, etc.). For that reason, there physical form factor usually mirrors conventional lead-acid batteries.

Lithium-ion batteries work in the same way as conventional batteries in that current is produced by the flow of ions between cathode and anode, but as the name implies, ions are sourced from lithium rather than a lead alloy [22]. In the specific case of LiFePO4 batteries, iron phosphate is also combined with lithium on the cathode and the anode consists of graphite with some metallic backing (Figure 2.15)[42]. Lithium is a very light metal and has a high electrochemical potential, all of which means that these batteries have a substantial energy density and weigh roughly 50% less than AGM batteries of similar capacity [44]. This composition also makes it much less sensitive to temperature extremes; particularly cold weather where AGM batteries do not operate well.

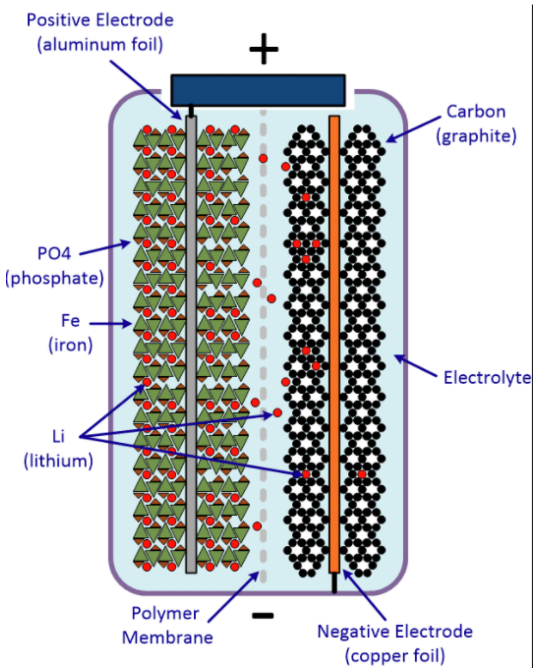

Figure 2.15. Illustration of the chemical reaction in LiFePO4 batteries [43].

The real reason why LiFePO4 batteries are able to take the place of AGM/lead-acid batteries though is because of its power density. Like its competition, low internal resistance equates to the ability to support large current demands, so these work well in the same applications [44]. The real benefit of LiFePO4 over AGM batteries though is its lifespan. These batteries are also considered batteries, but these are specifically used for constant discharge applications and have a life span of 2,000 - 10,000 cycles (depending on depth of discharge again) [42]. Not only that, but the voltage discharge curve is flat and can supply constant voltage until its total Ah capacity is depleted (see Figure 2.16 for comparison). The *c-rate* (speed a battery can be charged relative to discharged) of a LiFePO4 battery is significantly better than an AGM battery as well (10x).

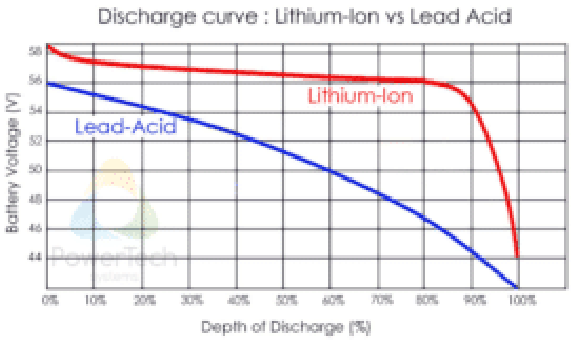

Figure 2.16. Comparison of discharge curves between LiFePO4 and AGM batteries [45].

The most major drawback of LiFePO4 batteries in comparison to AGM is the cost. Lithium batteries are composed of expensive materials and are a relatively new technology, so prices are roughly 4x AGM batteries. With that being said, LiFePO4 batteries are generally cheaper than some of the better performing lithium battery types. One of the other major justifications for this cost is the Battery Management System (BMS). Lithium batteries can be dangerous and catch fire when overcharged, so most lithium batteries come equipped with some form of BMS; a small PCB board that regulates charging of each cell.

Custom Lithium Cell Battery Pack

With the growing availability of lithium-ion batteries, hobbyists have harnessed the opportunity to create their own custom battery packs for numerous applications ranging from phone chargers to entire electric cars. Although many utilize whatever is readily available, the most commonly sourced battery type is the 18650 cell. This number refers to the cells dimension (18mm diameter, 65mm long, and 0=cylinder) [1]. The main appeal for these is their price and availability. These cells have been utilized in everything from rechargeable flashlights to Teslas for years and entire companies have been built around recycling and selling them at a discount.

Nominal voltage for these type of cells are 3.7V, but they are available in numerous parameters/compositions depending on the manufacturer. The accumulator options are endless when combining these cells in series/parallel. Figure 2.17 depicts a common example of an 18650 battery pack (3s5p...3 cells in series and 5 in parallel) with the inclusion of a BMS.

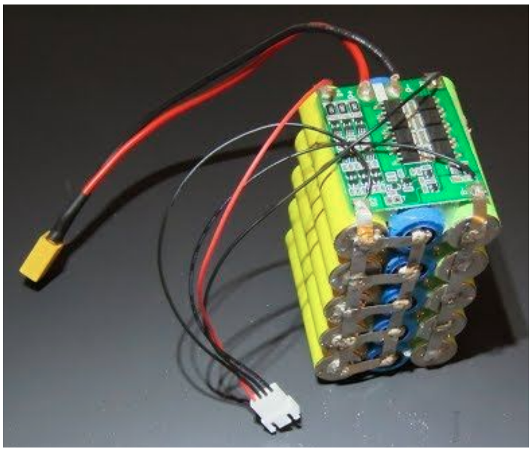

Figure 2.17. Example of a custom lithium-ion battery pack made of 18650 cells [25].

The biggest advantages of 18650 cells for an accumulator is the versatility and cost. By combining smaller cells that are hand-picked, the power source can be built to meet any voltage, capacity, specific power, or any other specific requirement. Also, by purchasing recycled cells or buying in bulk, accumulators can be built cheaper than using purpose built LiFePO4 batteries and outperform.

From the same source of the advantages stems some disadvantages. This modular approach also demands some specialized equipment to build and a substantial amount of time to create. A spot welder is needed to safely attach the conductive strips that connect the individual cells and an appropriate BMS also needs to be sourced. The work of attaching these cells together can be tedious in larger projects and the safety/reliability of the accumulator is ultimately decided by the diligence of the technician. In general, these types of cells are also more volatile and prone to combustion than LiFePO4 batteries [33].

2.3.3 Drive-by-wire Systems

Due to the autonomous nature of this project, a drive-by-wire system will be a must. Such a system replaces traditional mechanical and/or human-machine interfaces with a system of electromechanical actuators for steering. The following section explores some current marine steering systems and other pertinent methodologies of electromechanical actuation.

Boat Steering Hydraulics

Hydraulic drive-by-wire systems utilizes hydraulic actuators to control the steering. Modern versions of this include electro-hydraulic power steering(EHPS) where the hydraulic pump is controlled by an electric motor. This have been used for a long time in the automotive industry to improve the stability and ease of control over the steering. For the same reason as in the automotive industry, hydraulic cylinders have been used to control the steering of the boat engine and alleviates much of the physical effort that is associated with traditional cable driven boat steering. Typically this is a common solution for steering boats equipped with high torque engines or in the case where multiple engines are mounted in the stern. This is also the type of steering mechanism that is currently used by Candela.

Although hydraulics offer many benefits over cable driven systems much of the preferred way of implementing a steer-by-wire system is to remove the hydraulics and instead control the steering directly with a purely electrical system. The benefit of that is that an electrical system is using fewer moving parts and removes the hydraulic pumps and fluids which makes a simpler system to control.

Electrical Power Steering

Electrical Power Steering (EPS) are a common alternative to hydraulically controlled steering and utilizes a system of motors, gears and angle sensors to control the steering. This is a common concept applied to modern cars as it allows a central computer to control the steering which makes it possible to include systems like the auto-pilot and traffic accident avoidance systems.

One interesting showcase of the EPS system are the ABB azipod thruster. The azipod is a version of a broader variatey of motors called azimuth thrusters that are able to turn 360 degrees around its vertical axis. A common setup is to equip vessels with a pair of azimuth thrusters in which the 360 degree control gives the the ship great manuverability and are a common soloution for creating dynamic positioning systems. The azipod is a gearless electric propulsion system that can be fully integrated into a submerged pod [64]. The thruster is divided into a propulsion and a steering module. The steering module is using designated steering motors that are responsible for controlling the angle of the propulsion motor. This is done through connecting the steering motor to the propulsion module through a set of pinions, a gear rim, a slew bearing and a slipping unit, which allow the 360 degree rotation.

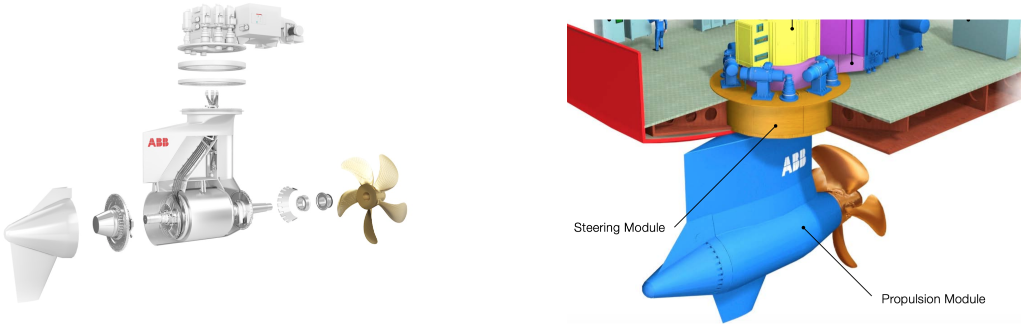

Figure 2.18. Assembly of the ABB azipod (L) and the steering and propulsion module (R) [64].

The azimuth thrusters are usually designed in the power ranges of 1-22MW systems which is targeted to mainly equip large surface vessels. The steering module used in the azipod can however be scaled down to match a smaller propulsion system with the use of a servo or stepper motor. This is common in RC boat application. While stepper and servo motor are both similar in that they can be used in similar applications, there are however some key differences dividing the two.

A stepper motor is a Brushless DC Motor (BLDC) that rotates in a set amount of steps. A permanent magnet rotor is surrounded by a set of windings (stators), that when current is applied in a set order defined by the motor driver, makes the rotor rotate in incremental steps. This means that the stepper motor can run in ”open-loop”, since it is possible to keep track on the amount of steps moved without feedback. However, when stepper motors carry a load, it is possible that they slip and miss a step every once in a while. Usually this isn't a problem due to one step being very small, but for applications where the position is crucial, it can be a good idea to run the stepper motor in ”closed-loop” instead by using an external encoder that provides angular feedback. Another key characteristic of the stepper motor is it's high holding torque. Current runs through the stators, even at rest, which allows a stepper motor to keep its position very well. However, this torque falls off as speed increases [20].

A servo motor on the other hand cannot be run in open loop since it relies on a feedback device to read parameters, such as torque, motor velocity, voltage and current level. Due to this, they are very accurate at high speeds and will produce a fairly constant torque output. Due to the need of feedback control and the need of position feedback, servo systems are usually more expensive [23].

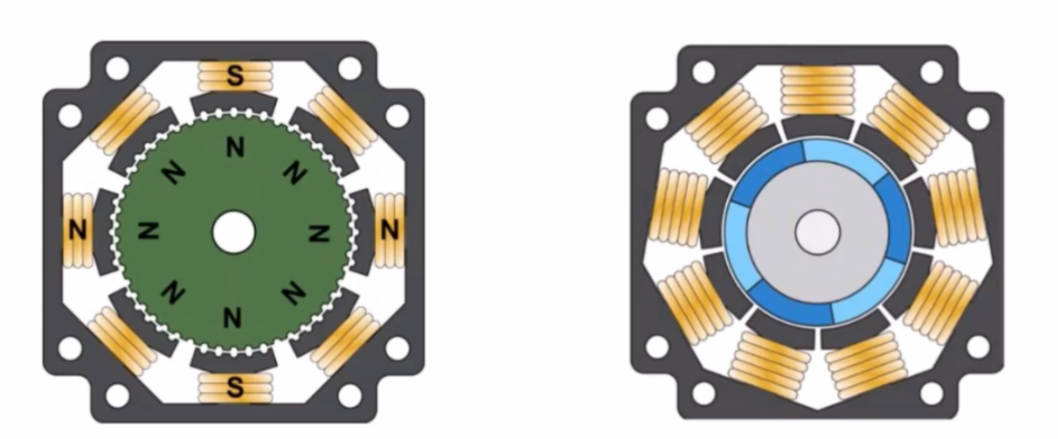

Figure 2.19. Stepper motor(L) and servo motor(R), steppers have up towards 100 poles where servos have a maximum of 12. [75]

Electronically Controlled Trolling Motors

Some higher-end trolling motors are equipped with a drive-by-wire system of their own rather than requiring the physical input of an operator. This is often achieved with a small DC motor that is mated to the shaft via a gear and operates at the same voltage as the larger motor. Minn Kota takes this same approach with their Terrova series of motors as seen in Figure 2.20 [81]. These types of motors are usually reserved for bow mounting useage (in the front of the boat) due to their size.

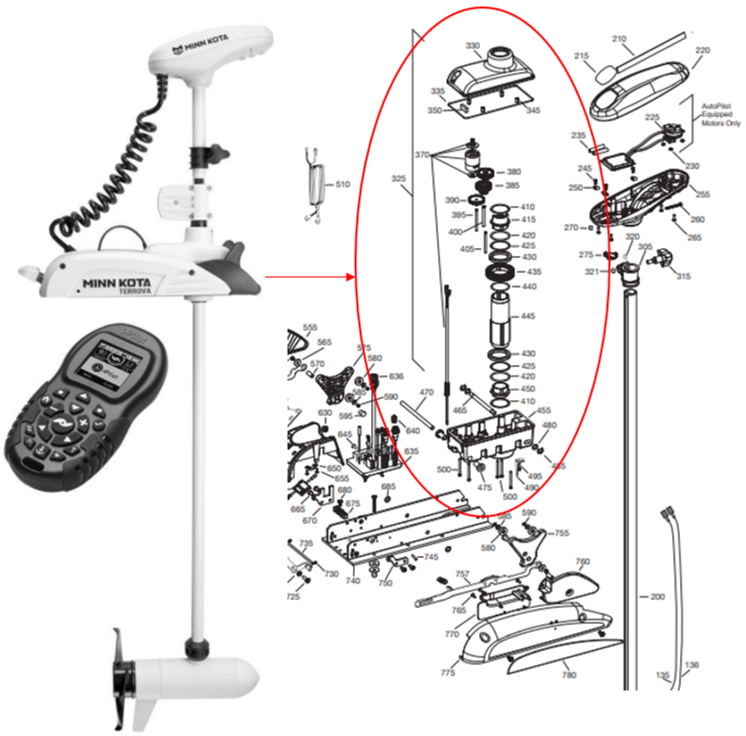

Figure 2.20. Minn Kota Riptide Terrova exploded view [81].

Often times, these smaller DC motors are then controlled with a Bluetooth handheld or foot control that allow operators to adjust the desired angle with little effort. In the case of the Terrova, it is even equipped with Minn Kota's "i-Pilot" system which includes GPS and allows for inputting of way points and heading cruise control. Other competitors offer similar functions as well.

Such products provide a large range of functionality, but come at a premium price point. Most of these enhanced trolling motors start at 14,000 kr. These drive-by-wire solutions are also comparatively slow to those used in other industries and/or applications. Trolling motors are used as a secondary motor, usually for the sole purpose of moving a fishing line through the water. For that reason, the application only requires slow movement and maneuverability is not a concern.

2.4 Modelling of Marine Crafts

The equations that describe the dynamics of ship manoeuvring are complex. Hence, when modelling marine crafts, simplifications are done and only a limited range of operational conditions are considered [9].

2.4.1 Coordinate System and Vector Notation

Many different types of reference frames exist but in this project two ones are mainly of interest: the North-East-Down (NED) coordinate system and a body-fixed frame of reference.

NED frame

The NED frame has the origin defined at a fixed point relative to the earth surface and has axis pointing in the North, East and Down directions [83]. For marine craft operating in a local area, with approximately constant longitude and latitude, an Earth-fixed tangent plane on the surface is used for navigation. Usually, this is referred to as flat Earth navigation and is for simplicity denoted by subscript n [15].

Body-fixed frame

A body-fixed frame has the origin defined at a point fixed to the moving vessel and has axis pointing in surge, sway and heave directions [83], as displayed in Figure 2.21. The position and orientation of the craft are described relative to the inertial reference frame while the linear and angular velocities of the craft should be expressed in the body-fixed coordinate system. The body frame is denoted by subscript b [15].

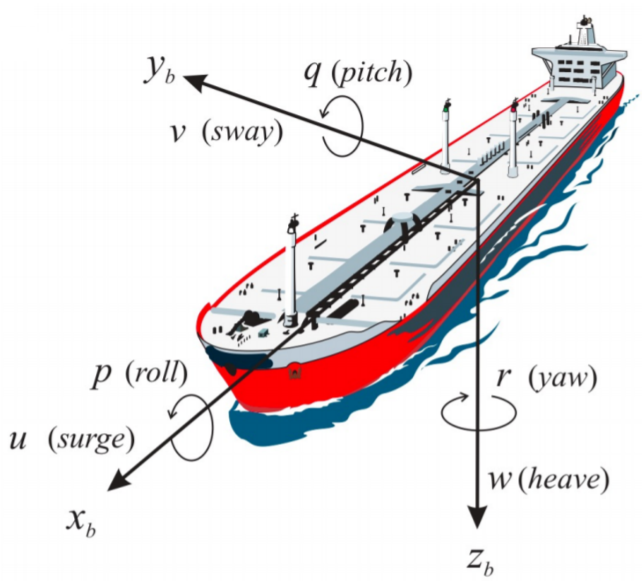

Figure 2.21. The 6 DOF velocities of a ship [15].

2.4.2 Kinematics

The kinematic equations of motion for a general 6-DOF marine vessel is derived and written in vector notation as [15]

$$\dot{\eta} = J_k(\eta)\nu \tag{2.1}$$

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) + g_0 = \tau + \tau_{env} \tag{2.2}$$

in which

- η is a vector containing the position and orientation in the NED frame,
- ν is a vector containing velocities in the body-fixed frame,
- $J_k(\eta)$ is a transformation matrix depending on Euler angles and maps the velocities in the body-fixed frame to the NED frame,
- M is the system inertia matrix, including added mass,
- $C(\nu)$ is the Coriolis–centripetal matrix, including added mass,
- $D(\nu)$ is the damping matrix,
- $g(\eta) + g_0$ are gravitational/buoyancy and hydrostatic forces and moments,
- τ is a vector of control inputs such as thruster forces,
- τ_{env} is a vector containing enviromental forces such as forces from the wind, from waves and from water currents.

Low speed model simplifications

By assuming that the pitch and roll are small, which is a good approximation for most conventional ships, underwater vehicles and rigs [15], and by neglecting the heave, since for a surface vessel the heave motion is not controllable [62], the general 6-DOF model may be reduced to a 3-DOF model only describing the horizontal motion (surge, sway and yaw) of the vessel. Under the assumption of low speeds, the model may be simplified further by neglecting the impact Coriolis and centripetal forces [8] as well as assuming that linear viscous damping dominates [83]. This yields the resulting simplified system as

$$\dot{\eta} = R(\psi)\nu \tag{2.3}$$

$$M\dot{\nu} + D\nu = \tau + \tau_{env} \tag{2.4}$$

where D is the linear damping matrix and $R(\varphi)$ is the rotation matrix, which contains the surge, sway and yaw terms of $J_k(\eta)$, and is given by

$$R(\varphi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.5}$$

This simplified model is hence described as the one displayed in Figure 2.22.

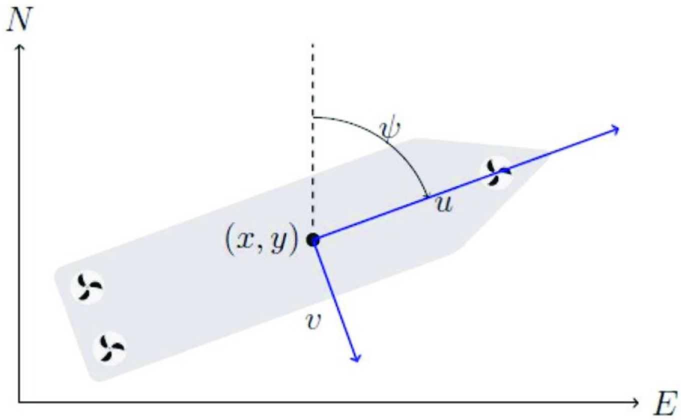

Figure 2.22. Schematic figure of the 3-DOF system model [53].

2.5 Positioning

An accurate position and orientation of the vessel will be needed during the docking. In this section, how this can be measured is presented.

2.5.1 Global Navigation Satellite System

GNSS is a constellation of satellites that transmits signals with positioning and timing data to GNSS receivers, in order to determine the location of said receiver. GNSS provides global coverage with multiple satellites. Europe has Galileo, The United States of America has GPS, Russia has Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) and China has BeiDou Navigation Satellite System [77]. GNSS requires a clear path and can easily be blocked by buildings and when travelling through tunnels. To combat this when developing Autonomous Road Vehicles, a technique called Dead Reckoning is used. It uses the last known location together with input from sensors, such as accelerometers, to calculate the change in location by estimating speed and heading. This is however not an issue when used together with naval vehicles since the signal is harder to block in open waters. Independent use of GNSS offers an accurate position within a couple of meters.

2.5.2 GNSS Correction Services

In order to increase the accuracy of GNSS, there are different correction services. Two of them are Differential Global Navigation Satellite System (DGNSS) and RTK. Correction data is sent with the Radio Technical Commission for Maritime Services (RTCM) protocol, which is sent with Networked Transport of RTCM via Internet Protocol (NTRIP). The GNSS receiver must therefore be able to operate with NTRIP in order to utilize correction services.

Differential GNSS

DGNSS is a technique were several GNSS receivers are used together to get a higher accuracy than independent use of only one receiver. The accuracy for DGNSS is around a meter, depending on equipment [39]. Therefore, it is not suitable for use with Autonomous Vehicles, which requires a much more accurate localization.

Network RTK

Network RTK uses a number of reference stations situated around the world, and provides the GNSS receiver with its true position by calculating its own error in position. This can be seen in Figure 2.23. This provides an accuracy of up to 30 mm if the receiver is within 70 km from a base station, and as low as 25 mm if within 35 km. SWEPOS is Lantmäteriet's support system for satellite positioning in Sweden and they provide a service for Network RTK. Network RTK uses a two-way transmission. When using a single temporary base station the communication can be done with Telemetry Radio, but SWEPOS requires an internet connection.

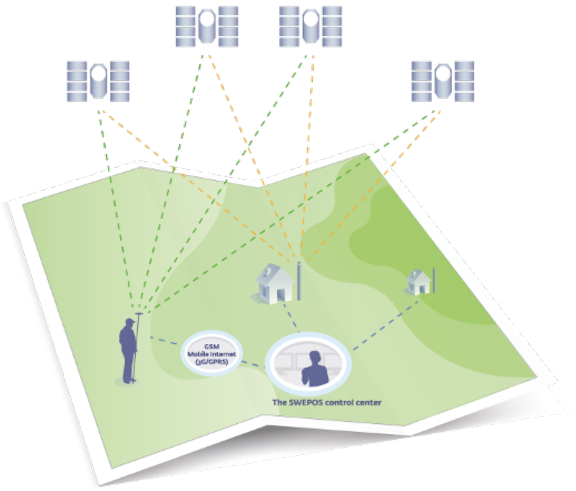

Figure 2.23. When measuring with network RTK, users send in their position to the service's operations management center and get back ”tailored” correction data for their position [38].

2.5.3 Heading

To determine the correct heading of autonomous marine vessels, some kind of IMU is often used. Standard IMU combine 3-axis accelerometers, gyroscopes and sometimes magnetometers as well. Sometimes a fully integrated electronic compass module is used, they combine 3-axis magneto-resistive sensors with accelerometers and are usually tilt-compensating the angular heading. This can provide an accurate heading within 1 degree.

2.6 Control Theory

In this section, control theory which is used in previous similar work, and most likely will come into play in this project, is presented briefly.

2.6.1 Hybrid Systems

Hybrid systems are systems which incorporate both continuous and discrete event models into it and are extensively used in air traffic management systems and for intelligent vehicle control [10]. As an example, the gear shift of a car could be modeled as a hybrid system, as displayed in Figure 2.24. Here, the position of the car on the road is denoted as x_1 and the velocity of it as x_2 and are considered outputs of the system. For inputs, the model has two control signals. The gear, denoted as **gear** $\in \{1, 2, 3, 4\}$, and the throttle position, denoted $u \in [u_{min}, u_{max}]$. The function α_i denotes the efficiency of gear i. The shifting of gear is necessary since little power can be generated by the engine at low or high engine speed [30].

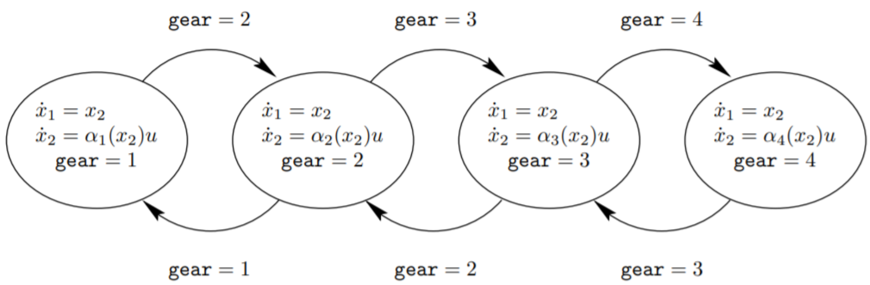

Figure 2.24. A hybrid system modeling a car with four gears [30].

Hybrid Automata

A formal way to model a hybrid system is to do it as a hybrid automaton. This is done as

$$H = (Q, X, Init, f, D, E, G, R) \tag{2.6}$$

where H is a collection in which

- Q is a set of discrete states,
- X is a set of continuous states,
- $Init$ is a set of initial states,
- f is a vector field,
- D is a domain,
- E is a set of edges,
- G is a guard condition,
- R is a reset map.

Also, $(q, x) \in (Q, X)$ is referred to as a state of H [30].

In an attempt to make this a bit clearer, an example is displayed in Figure 2.25 in which a transition, $(q, x) \to (q', x)$, is described. Starting from an initial state, $(q_0, x_0) = (q, x) \in Init$, the continuous state, x, evolves according to the dynamics described by the vector field, $f(q, x)$, while the discrete state, q, remains constant. This evolution can go on as long as x remains in the domain $D(q)$. Suppose then that, at some point, x reaches the dynamics of a guard condition, $G(q, q')$, than, the discrete state of the system may change according to the edge, E. In this case this would imply that the discrete state of the system changes from q to q'. At the same time the continuous state gets reset to some value which is described by the reset map, $R(q, q', x)$.

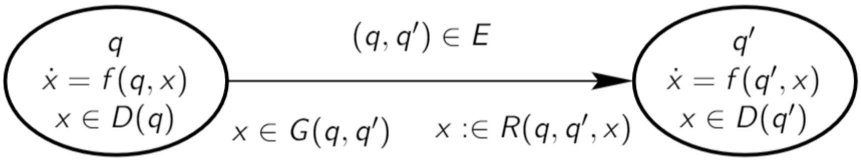

Figure 2.25. Example of a transition described by a hybrid automaton.

2.6.2 Controllers

The controllers commonly used for motion control of ASVs are mentioned in section 2.1.5. A combination of these control systems are used in hybrid systems, where they regulate different states of the vessels. A shorter overview of these types of controllers are given below.

PID Control

PID control is commonly used in feedback and feed-forward control. Here, the error between the output and input to the system is regulated to achieve desired output. Increasing the proportional part of the controller increases the speed of the system but is also more prone to introduce instability. The integrating part is used to eliminate steady state error in the output, but is also prone to introduce instability. The derivative part may be used to increase stability, though it is not unusual to omit this part since differentiating noisy measurements may be precarious [17].

Linear Quadratic Control

LQR is a type of optimal control. Simply put, the goal of LQR is to minimize the square of the error between the output and the reference as well as the square of the control signal. The regulator can also be extended to handle Gaussian noise [18].

Sliding Mode Control

SMC is a nonlinear control method which use high gain control to approach the sliding surface in finite time and then slide on the (stable) surface to approach the desired point. The method is robust to disturbances on the input and can be extended to be robust against model uncertainties. Typically for SMC is that the trajectory does not stay identically on the sliding surface and instead oscillates around it [34]. A typical SMC phase portrait is displayed in Figure 2.26.

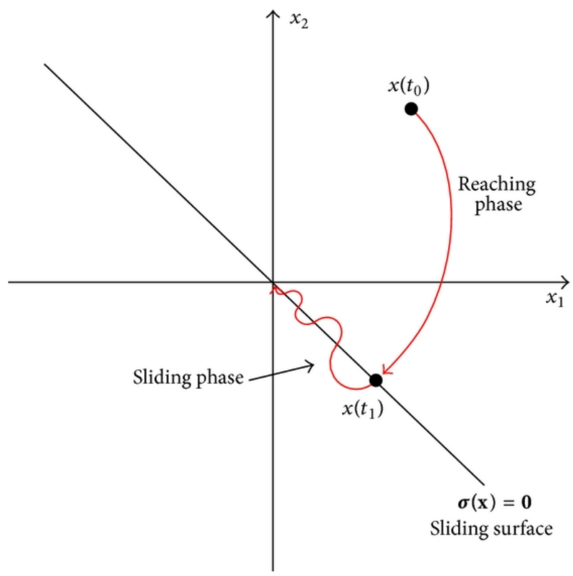

Figure 2.26. Typical Sliding Mode Control phase portrait [95].

Model Predictive Control

MPC uses the predictive power in a model of the controlled object to calculate the control signal. The control signal can be chosen so that a given criterion is minimized, subject to physically motivated bounds on the signals [18]. Simply put, MPC uses at each sampling instant the plant's current input and output measurements, the plant's current state, and the plant's model to calculate a future control sequence that optimizes a given performance and satisfies constraints on the control action as well as uses the first control in the sequence as the plant's input [5].

2.6.3 Kalman Filtering

Kalman Filtering, also know as Linear Quadratic Estimation, is used for sequentially estimating the states of a linear Gaussian dynamical system. The algorithm used has a low computational complexity and can therefore be implemented for real-time applications [36]. KF is used to solve a large variety of problems, one example is loss of signal with GNSS applications where dead reckoning is used, as mention in Section 2.5.1. The way KF work is recursively. As displayed in Figure 2.27, where a simplified overview of the algorithm is shown, the algorithm consists mainly of two parts, the prediction step and the correction step. Firstly, a prediction of the system is made based on what inputs are available. Then, based on measurements, correction is made to the prediction. This is then iterated until the prediction is sufficiently accurate [11]. Though KF only can be used on linear systems of equations, it can be extended to work with nonlinear systems. The KF is then instead called an EKF and this is done by utilizing Taylor series expansion on the nonlinear system to be filtered [34].

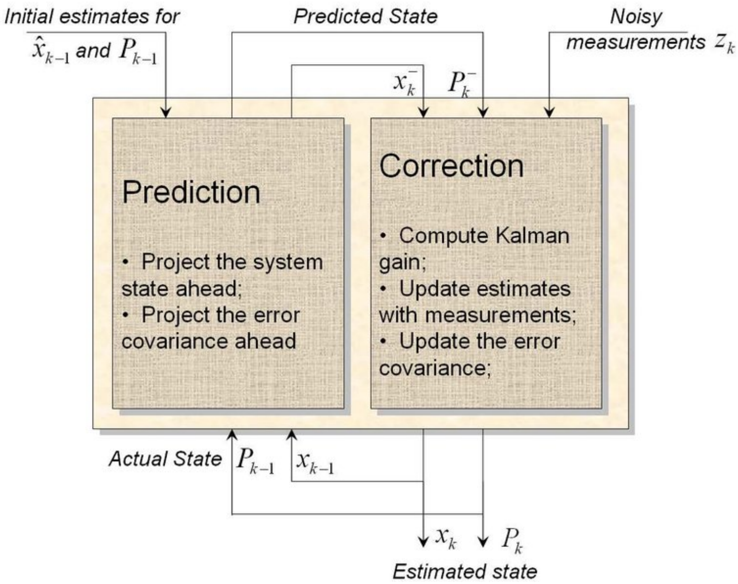

Figure 2.27. Prediction/Correction algorithm cycle of the KF [72].

2.6.4 Path Planning

Path planning can be defined as the problem of finding a route between two positions in a mobile space whilst taking into account that the route should be collision-free, physically feasible within spatial constraints as well satisfy certain optimisation criteria. Commonly, these optimisation criteria for path and trajectory planning include minimisation of path length, time, and energy consumption, as well as measures of safety or risk. Path planning is typically defined solely within geometric space whereas trajectory planning has a wider scope and includes dynamics such as angle limits, velocity and acceleration constraints. As for path planning algorithms, they could be classified into taking one of three approaches [85].

An algorithm taking a classical approach involves firstly to model the environment and the secondly to perform a search for the optimal path in this environment. This approach is suitable where there is no need for path re-planning or local collision avoidance. An advanced approach is taken when dealing with dynamic obstacles, path re-planning or local collision avoidance in real time and often do not require environmental modelling beforehand. These approaches include machine learning algorithms, potential field methods and velocity space methods. As for hybrid approaches, these include algorithms which include several different path planning algorithms [85]. Displayed in Figure 2.28 is an example of a potential field method, where the goal is given attractive potential and the object in the way is given repulsive potential. This makes the vessel moving trough the plane move to the goal while at the same time being repelled by the object [12].

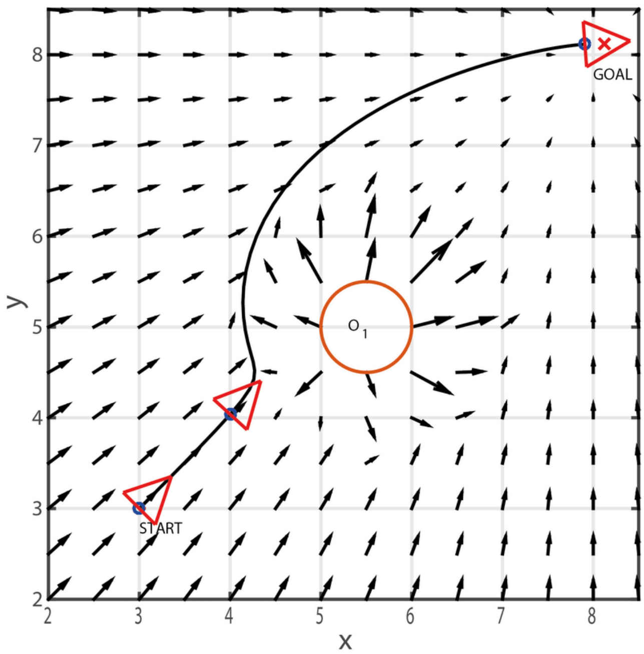

Figure 2.28. Example of artificial potentials path planning [14].

2.7 Dock and Obstacle Detection

The Dock and Obstacle detection subsystem has two main purposes. The first is to be able to detect and localize the dock. The other is to detect and localize obstacles on the way there. In this section hardware and software that would enable fulfilling those two purposes was investigated.

2.7.1 Hardware

To be able to detect objects, sensors that can interpret the surroundings is needed. In similar projects as seen in Section 2.1 the way this has been done is using sensors like LiDAR, Stereo Cameras and/or Radar. In this section these sensors will be presented and explained.

LiDAR

LiDAR utilizes laser light pulses to measure the distance to surrounding objects (see an illustration of this in Figure 2.29). To get these distances the Time-of-Flight

(TOF) is measured, in other words the time it takes for the beam to hit the surrounding and return. The distance can then be calculated by multiplying the time of flight with the speed of light and dividing it by two to get the one way distance[76].

The main advantages of LiDAR is the accuracy. The short wavelength of LiDAR enables it to detect small objects at a far distance. A LiDAR with a wavelength of 1500 nm is possible to accurately detect an object the size of a tire at a distance of 150 to 200 meters [60]. Another big advantage for the LiDAR is the possibility of a 360 Field of View (FOV). Enabling the sensor to detect obstacles all around the vessel [28]. Another trait that speaks for the LiDAR is that its not dependent on good lightning conditions. Since it sends out it's own light it operates well during the darker hours too [94].

The LiDAR also has it's down sides. The biggest disadvantages with LiDARs is the hefty price tag. Even though the price has come down in recent years a 3D LiDAR with 360 degree FOV can cost anywhere from 35 000 kr to 150000 kr [55]. Another drawback with LiDAR is its performance in bad weather [94]. The rain makes the surfaces that the LiDAR beam bounces of wet and because of this the surfaces becomes less reflective. As a result the range at which the LiDAR can operate in reduces. At a precipitation of 25 mm/h the effective range can be reduced by up to 20 percent. Another way that the LiDARs effective range can be reduced is in the case of foggy weather. The small droplets caused by the fog makes the beams scatter. The scattering of the beams reduces the operational range of the LiDAR by up to 50 percent. [7] .

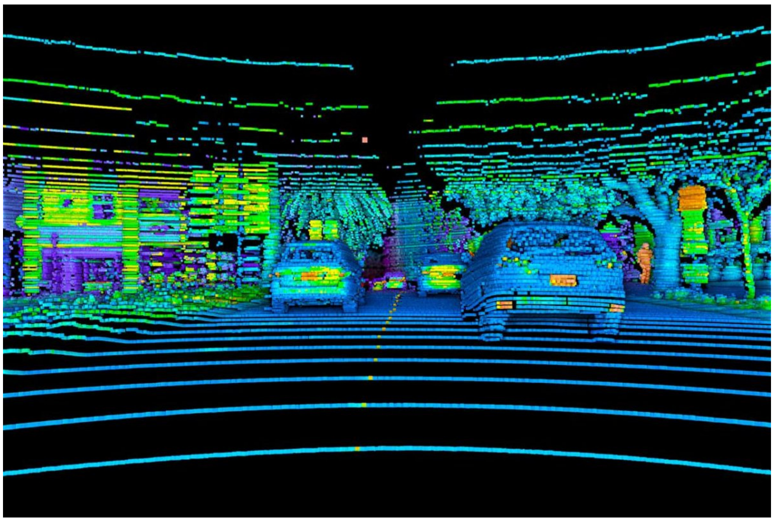

Figure 2.29. Visualization of LiDAR mapping [41].

Stereo Vision

Stereo vision is a technology utilizing two passive visible light cameras. The cameras are positioned a known distance from each other and have a parallel viewing direction. The distance to points in the image is calculated by comparing the two images and measuring the disparity between the two. As you can see in Figure 2.30 both cameras capture C and D. Then the parallax between what each camera sees makes it possible to calculate the distance to C and D.

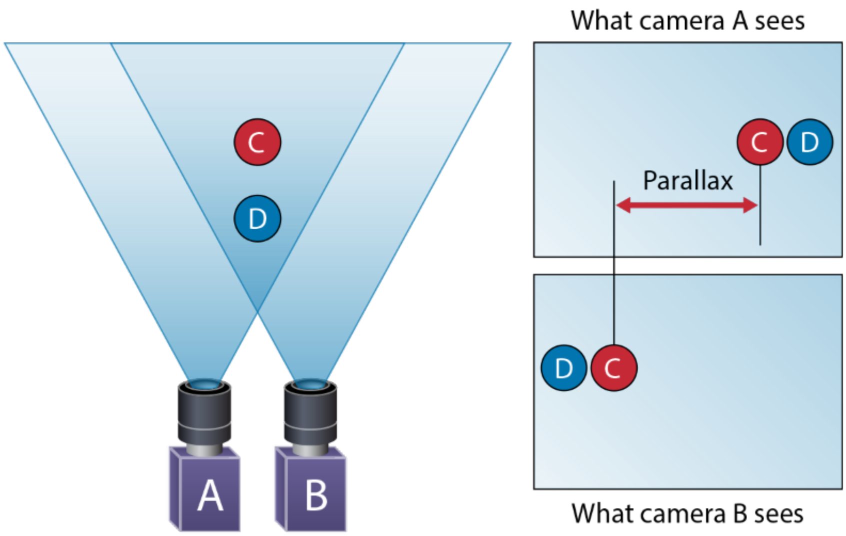

Figure 2.30. How the distance is derived with two cameras [24].

One of the advantages with using a stereo camera is the possibility to use algorithms to enhance the visuals. These algorithms can be used to improve the detection in for example bad weather situations. Improving the detection will as a result also improve the operational range. As shown in this paper an effective object detection can still be achieved in rainy condition if a visual post processing algorithm is applied [16]. Another paper found that the same concept can be applied in foggy weather. If the image is post processed a good object detection can be accomplished in foggy conditions as well.[32]

The stereo cameras have qualities that are advantageous, but it also has its downsides. One of the main limiting factors of a stereo camera is localization range. The distance of which the cameras can detect objects depends a lot of what FOV, but as an example the ZED 2 by Stereolabs has a FOV of 110 degrees and a range of 20 m [78]. Something that must be considered when using a stereo camera is the need for good external lightning. Since the cameras are only passive and do not produce any light on there own the surrounding needs to be well lit.

Radar

Radar is a well known technology with a lot of variation. Common of all radars is that they send out electromagnetic waves and then receive the reflected response. Radar frequencies can range from 5 MHz to 130 GHz [93]. So called millimeter wave radar is commonly used in ranges of up to 100 m, which is applicable in this project. Millimeter wave radar commonly has a frequency of about 75 GHz. The specific radar technology used in these types of implementations is called Frequency-Modulated Continuous Wave (FMCW). It is a strategy for obtaining accurate radar distance measurements based on modulating the frequency of the signal in a repeating wave pattern [92]. The shape of the signal wave can take on many different shapes, a saw-tooth configuration for example gives the best range capability while a square wave has shorter range but higher accuracy. An example of a saw-tooth wave can be seen in Figure 2.31, the horizontal axis is time and the vertical is frequency .

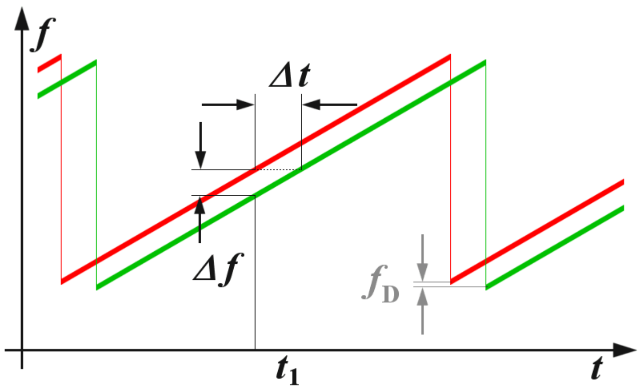

Figure 2.31. Example of a FMCW waveform [92].

The distance to an object is calculated based on the time-shift Δt between the outgoing and the received signal. See Equation 2.7, where R is the distance in meters and c_0 is the speed of light in m/s.

$$R = \frac{c_0 \Delta t}{2} \tag{2.7}$$

2.7.2 Real-Time Detection

Markers

Usage of some kind of marker attached to the dock was investigated. The advantage of some kind of marker is that the vision detection problem is greatly simplified.

One can even go a step further and use a localization tag like the AprilTags, see Figure 2.32, developed by the University of Michigan [84]. A predefined tag has the benefit of being of a known shape and size. This gives the vision system the ability to relatively easily determine the distance and angle to the tag based on the perceived size in the cameras field of view. A tag can also be scaled up almost indefinitely to increase the range of the location system.

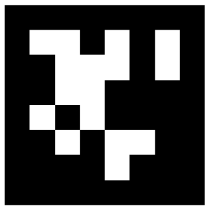

Figure 2.32. An example of an AprilTag [84].

Template Matching

Template matching is a technique within computer vision that uses templates to find objects in images. These templates can be features of the object you want to detect or the whole object. The idea is that with a template scan through the image and with different techniques determine the likelihood that the object is in the image. As an example of template matching you can see in Figure 2.33 were the cup is the template and the image in the middle is the image we want to scan for it [79]. One of the big advantages with using template matching is that it doesn't

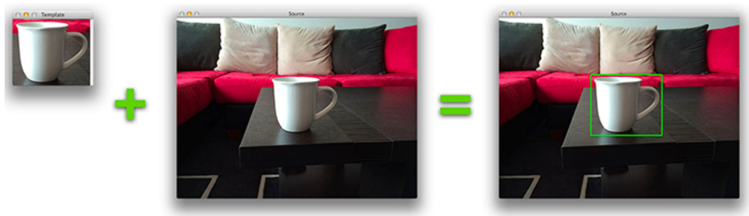

Figure 2.33. Example of template and image to match it with [74].

demand any training. The matching is done at runtime and even if it sees the same image multiple times it will still give the same output. This is also one of its biggest weaknesses since the algorithm doesn't learn from its mistakes and improve over time [29].

Image recognition with Neural Network

Image recognition in deep learning is used for identifying images and categorizing them in predefined and pretrained classes.

Image recognition can be implemented using a Convolutional Neural Network (CNN). The CNN will give a probability score for every predefined class and then determine which label most likely applies for the given image input. Depending on the implementation, the CNN could give a label for the image as a whole or it could divide the given image input into various sections for detecting multiple classes in one image. When dividing the image into sections it also becomes possible to get the position of the class in the image. An example of this can be seen in Figure 2.34.

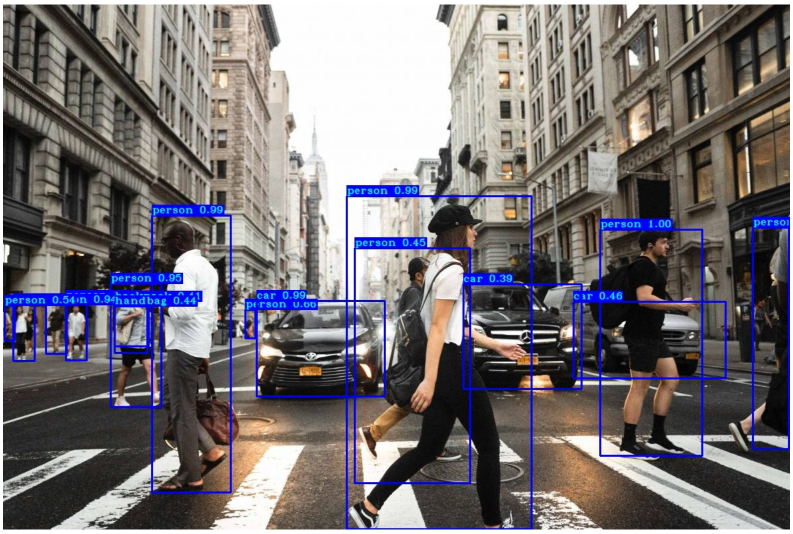

Figure 2.34. Example of image detection using the YOLOv3 algorithm [13].

Neural networks have achieved promising results in various fields of pattern recognition, not only image recognition but also fields such as voice recognition, determining/predicting weather and advertising [2].

A neural network consist of nodes (also known as neurons) that are placed in layers. The layers are placed in a sequence and the every node in each layer have a connection to every node in the next layer in the sequence as seen in Figure 2.35.

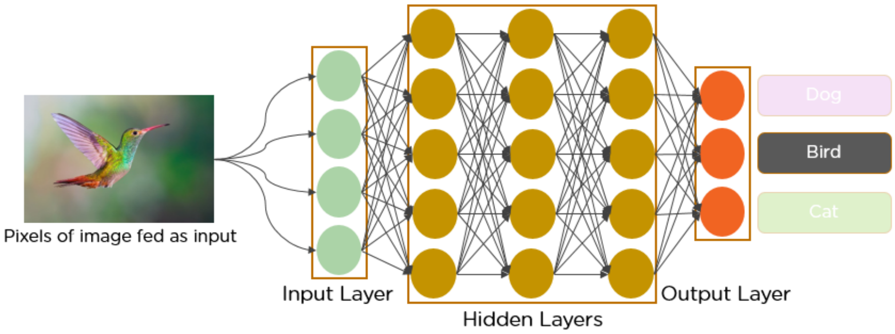

Figure 2.35. Example of a Convolutional Neural Network [49].

In a way, a neural network attempts to imitate the way a brain works. Each of the connections between the nodes have a parameter called a weight which is one of the main parameters to be tweaked during training and to infer a prediction from the given input data. Since every node is connected between the layers, there will be a lot of parameters to take into account both when making a prediction and when training. For example using a small 32x32 color image, there would be 3072 weight connections for every new node that the input layer is connected to. So if the second layer has as many nodes as the input layer, that would mean 3 145 728 connections between just two layers. A more efficient method for connecting layers than fully connecting them is to introduce convolutional layers which looks at local regions of an image and not the image as a whole. It could for example connect to 5x5 neurons and keep the local connection weights fixed, dropping the number of weights to only 5x5x3 = 75 [4]. These convolutional layers are great at detecting patterns, making it a good choice for image recognition [4]. Although the number of weights can be dropped, inference and training can still take a long time, a good GPU can be used for making the process faster [54] and making it more viable for realtime detection.

YOLOv3 is a state of the art algorithm for detecting objects in real time using 106 fully convolutional layers [68]. The YOLO algorithm generates bounding boxes around a prediction and also provides probabilites for each bounding box. The algorithm also uses non-max suppresion to make sure that each object is only detected once. Using an Nvidia Titan X graphics card and an input resolution of 256x256, YOLOv3 was able to run at 78 frames per second [68]. This is actually slower than the previous version, YOLOv2, but v3 has an increased accuracy.

Data augmentation for training datasets

Large datasets are usually required when training a neural network. The more complex the network is, the more parameters there are to train. This means that more data is likely to be required for training the network. Training a CNN on a small dataset can make it prone to overfitting leading to it being very inaccurate on unseen data and only making it accuracte on the training data [80]. This could cause issues when the available data is limited or if there is not enough resources or time to collect data. A way to solve limited datasets is to use data augmentation to increase and diversify the dataset without actually collecting more data. An example of a basic augmentation can be seen in Figure 2.36.

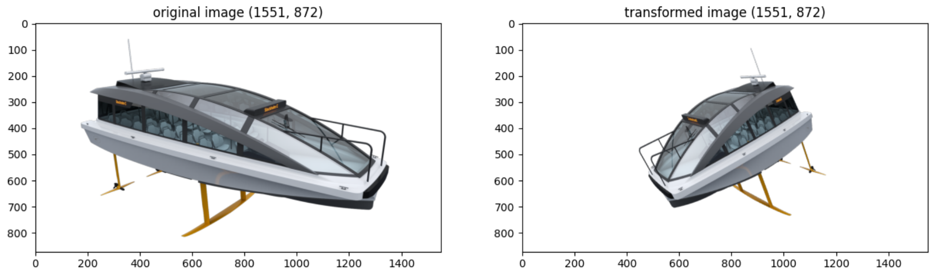

Figure 2.36. Image transformed by flipping it, giving it a random rotation and warped perspective.

Experiments have shown that by purely using cropping augmentation on a dataset, the accuracy can be improved from 64.5% to 79.1% [80].

Computing

As mentioned in section 2.7.2 a CNN requires a lot of computing power for both training and inference. For training the CNN an option could be to use Google Cloud. This service provides access to a remote computer with great computing power. The GPUs that Google Cloud offer are Nvidia K80, P100, P4, T4, V100 and A100 [19]. The GPUs available at Google Cloud are specifically designed for performing simulations and large-scale calculations.

While running inference however, Google Cloud would not be an optimal choice if real time detection is desired. The reason for this is that Google Cloud runs on a remote computer which means that there would be delays and a stable internet connection would always be required for transferring. Nvidia offers a series of embedded computing boards called Jetson. Jetson are specifically designed for accelerating machine learning applications and is a low-power system. For example the Nvidia Jetson Xavier NX runs on 10W and the onboard GPU has 384 CUDA cores and 48 Tensor cores [61].

2.8 Near-Field

The main purpose of this subsystem is to highly accurate assist the boat during the final meters of the docking procedure and also to ensure contact to the dock during embarkation/disembarkation. Additionally, it is also supposed to be able to detect any hazards within close range around the boat. In order to fulfil this, a number of sensors and solutions were investigated.

2.8.1 Proximity sensing

As there are many options for proximity sensing, the main inspiration for the possible sensor solutions were taken from the automotive industry, which utilizes ultrasonic sensors and mmWave radar to a high extent.

mmWave Radar

As mmWave radar operates in high frequencies as presented in Section 2.7.1, it's able to detect movements that are a fraction of a millimeter within a range from a few centimeters up to over 100 meters, depending on object [69]. It can provide range, velocity and angle to the detected object. This is done by measuring the time for the optical signal to return, how the signal has changed from the reflection and how the phase shift between in- and outgoing signal differs. The mmWave radar is also impervious to environmental conditions such as sunlight, rain, fog, dust and snow and can penetrate most materials except metal, making it possible to be mounted behind surfaces without needing a clear line of sight [69].

Ultrasonic sensor

An ultrasonic sensor detects the presence of an object and measures the distance to it, without making physical contact. The effective measuring range in air is from a few centimeters up to several meters, depending on exact sensor and object properties. The sensor generates and emits ultrasonic pulse waves that are reflected back by an object and captured by the sensor, as seen in Figure 2.37. As the speed of sound is a known variable, the sensor can capture the time difference between it's emitted and received echo signal, which is called a TOF measurment. The TOF can be used to calculate the distance between the sensor and the object accordingly to Equation 2.8, where t_r is the round-trip time and $v_s = 343m/s$ is the speed of sound in dry air at 20°C.

$$d = \frac{t_r v_s}{2} \tag{2.8}$$

Ultrasonic sensors can detect any object regardless of shape, transparency and color with the requirement that the material of the object is solid or liquid, i.e. non-sound absorbent [59]. However, the heading angle and object shape decides how well the object will reflect the ultrasonic waves. Round or tilted object may scatter a majority of the waves transmitted to the object, see Figure 2.38. This means that the object of interest preferably should be large, dense, flat and smooth, facing the sensor at a 90° angle to yield the best sensor response [59]. Ambient conditions as temperature, humidity and debris is also a factor needed to take into consideration. Dust, rain, snow could alter the sensor field-of-view and disturb the performance. If the sensor would be partially submerged in water or covered by snow, mud or ice, ranging performance could be reduced.

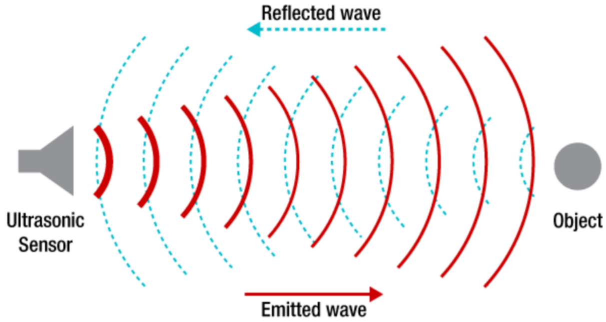

Figure 2.37. Ultrasonic sensor waves [59].

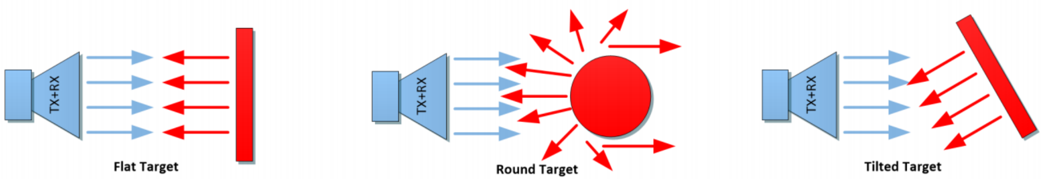

Figure 2.38. Round and tilted targets may scatter the waves. [59].

2.8.2 Dock contact sensing

To determine if the boat is in contact and stays in contact with the dock, the option of using load cells were investigated.

Load cell

The purpose of a load cell is to measure force and transform it into some readable information, usually an electrical signal. There are many different types of load cells and the range of measurable load varies a lot [91]. Some sensors types for larger loads are hydraulic and pneumatic. They use liquid and gas within the sensor and a pressure gauge measuring the pressure due to the load. There is also capacitive load cells for smaller loads. These contains two flat plates functioning like a capacitor. When the plates are pressed together the capacitance change it can be re calculated the the load upon the sensor. One of the most commonly used type of load cell uses strain gauges. The gauges change resistance when in strain and by measuring the change, the load can accurately be determined.

Also within the stain gauge load cells there is a great variety of cells. Still they all use the same technique, by sticking the strain gauge to a strong but elastic material such as steel or aluminum, the cell can bear a lot of weight and only temporally deform slightly. [21] That causes the resistance in the strain gauge to change, see Figure 2.39. The resistance change is very small, but by putting the strain gauge in a Wheatstone bridge, the resistance change can be measured very accurately. The slight resistor change gives sensor output in millivolts. To be able to read the analogue voltage output signal, the sensor may be connected to an A/D converter. A/D converters does not always have high enough resolution to register every mV shift, and differentiate it from other noise. In those cases a load cell amplifier may be used. The amplifier receive the mV, and amplify it to 0-10 V or 4-20 mA.

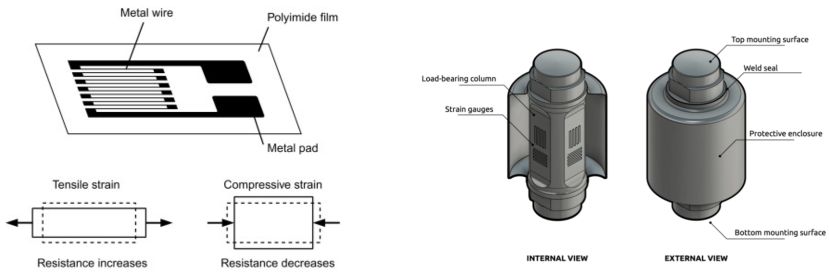

Figure 2.39. When the load cell is compressed, the resistance in the strain gauge will change [21] [82]

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Chapter 3

Concept design

This chapter describes the concept design and evaluation. It also presents the final concept and its specifications.

3.1 Concept Platform

In order to more easily realize the concepts, a boat hull will be purchased. The boat, a Kimple 330 Angler Wide, is a small aluminium boat and can be seen in figure 3.1. The boat is 3,3 m long, 1,37 m wide and has a weight of 56 kg [35]. This is small enough to be easily handled, but large enough to fit dual motors and the sensors required for autonomous driving. Its aluminum construction also makes it easy to modify and secure items to it.

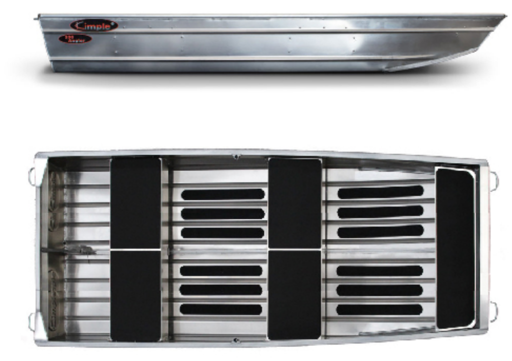

Figure 3.1. The proposed vessel to use as a platform [35]

3.2 Drive-by-Wire Design

Driving the vessel autonomously requires that the motors of the boat be controlled by a centralized computer. This is achieved by implementing some form of drive-by-wire control which utilizes an actuating system to control the motors. This entails a system that is able to control both the steering angle and the thrust of the motors. For portability to the P-30, this system is restricted to having both motors mounted at the stern of the boat with a maximum turning angle of ±30 degrees. From this, 3 concepts have been conceived.

Two out of said 3 concepts utilize some form of DC motor. It was decided that all concepts as such would utilize stepper motors specifically rather than servo motors. The reasoning for this is due to several factors. The motors will need to produce 3.5Nm of torque at minimum (based on some rough drag calculations) and will preferably not exceed 24V. This is too keep the overall cost of the accumulator down; the higher the voltage, the more batteries or boost regulators will be needed.

The key differences between stepper and servo motors are discussed in section 2.3.3. The main pros of a servo motor is that it can operate at high speeds, maintain torque at high speeds, and it has great positional accuracy at all speeds. This comes at a cost of higher voltage and amperage draw, as well as a much higher price though. For this application, the motors don't have to rotate any faster than ˜120 rpm to achieve a sufficient response time from -30 to 30 degrees (around 0.1 seconds). This means that a servo motor that can hold its torque for up to 4000 rpm is not needed since a stepper motor wont have significant torque drop until ˜300 rpm. To add, a ¿4Nm servo motor at 24V is a lot harder to find than its stepper motor competition. With all things considered, stepper motors are the better choice in this particular application.

In addition, it was established early on that all concepts conceived would have to incorporate some form of angle feedback via an encoder, potentiometer, or hall effect sensor. There is a need of accurate angle control in this application and there is a multitude of forces acting on the system due to it's maritime nature. Even though stepper motors are specifically used in open-loop cases where "steps" and holding torque are sufficient for maintaining position, these unpredictable forces may cause missed steps and inaccurate angle positions. Having some angle reading allows a control system to be built around that feedback and ensure accurate positioning at all times. An *absolute encoder* is also specifically preferred since it will retain positional readings even when powered off.

3.2.1 Direct Drive

The first concept, *direct drive* utilizes a hollow bore stepper motor that is attached directly to the shaft of the motor (Figure 3.2). This concept is beneficial for its ease of implementation and low cost. The hollow bore would also allow a handle to be attached to the end of the shaft which would make it possible to control the steering manually if needed. Components of the outboard motor could also be purchased separately (since the stock handled portion is no longer needed) and assembled, saving even more money.

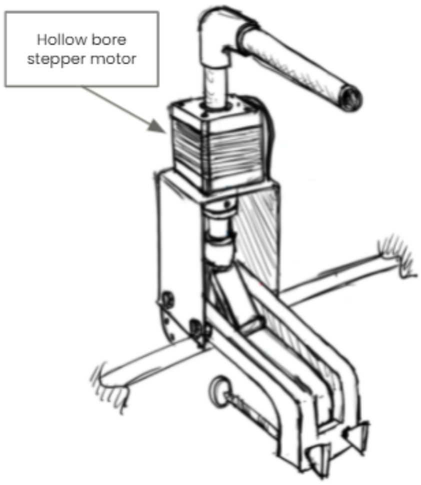

Figure 3.2. Direct drive concept sketch.

This approach may be limiting on the other hand. A direct configuration does not support the use of gears well (unless substantial time and money was spent designing a planetary system) and due diligence would then have to be done in selecting the motor. This is difficult though without knowing the rest of the prototype's parameters. In addition, hollow bore motors are far less common and have a limited parameter choices compared to normal stepper motors. This is especially true when considering that a ”closed-loop” stepper motor is desired (incorporated encoder with motor); these are even less available. A secondary sensor would have to be augmented onto the system most likely.

3.2.2 Geared Pulley

In the *geared pulley* approach, a standard closed-loop stepper motor is connected to an outboard motor shaft via a pulley system. The main advantage of using a system like this is in the ability to tailor the angular speed/acceleration of the outboard motor in relation to the the stepper. This is done by simply changing out the driven pulley diameter. Torque on the motor shaft can also be increased by simply placing a larger sized pulley on the motor shaft as well. Metal driver pulleys are readily available for standard stepper motor shafts, but the driven pulley on the shaft will most likely need to be fabricated by additive manufacturing created from a modified commercial item.

Tensioning of the belt will be done via the stepper motor mounting bracket that is secured on the boat hull clamp. The bracket can be moved back and secured with bolts, thus putting a load on the belt (see Figure 3.3). To prevent belt-slip, a toothed pulley will be used specifically. If testing shows this is still insufficient, an additional idler pulley can be explored as an option. This is unlikely given the expected speeds.

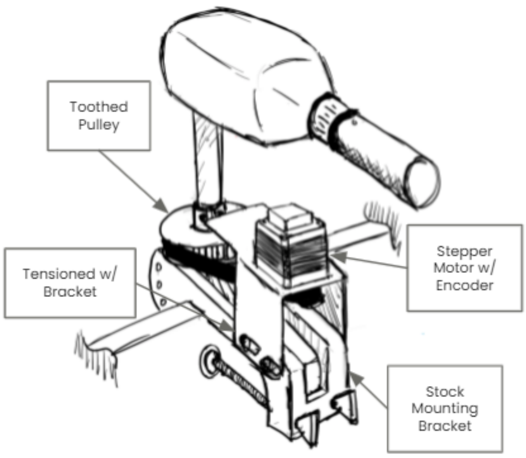

Figure 3.3. Geared pulley concept sketch.

The most prominent downside of this approach is the complexity. This concept has the most components of the conceived options and therefore will take somewhat longer to design and source hardware. This may also equate to cost as well, but it may also have little effect given that the stepper motor in this concept is generally cheaper.

3.2.3 Linear Actuator

This particular concept revolves around the use of a electric linear actuator. A linear actuator consists of some form of DC motor that is then connected to a lead screw directly or by the means of some gearing that then extends/retracts the actuator. This offers a large linear force that can then rotate the outboard motor when combined with a lever arm placed on the shaft (Figure 3.4. Beyond the large force, another advantage of this design is that these actuators are commonly found available with absolute encoders and that the system overall is easy to implement.

In this particular application, the idea is to design a bracket that can interface with outboard motor fixture with the intention of using additive manufacturing methodologies to create. See Figure 3.4 for a better idea on how this may look.

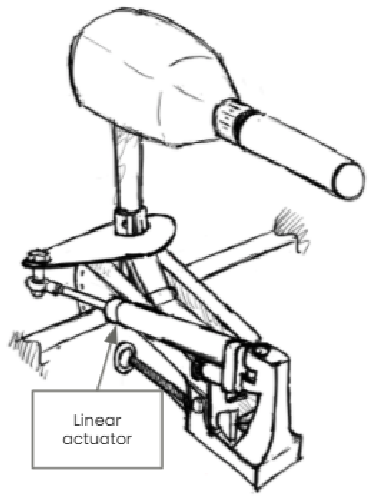

Figure 3.4. Linear actuator concept sketch.

Speed is the biggest draw back in this approach. Since the rotary motion of the DC motor is being translated into linear motion of the lead screw, speed is geared down. This may make such a concept too slow in responding to system demands. The footprint of this design is also much larger than the other concepts due to how it must be positioned. Another disadvantage is that torque applied to the shaft will not be consistent depending on the actuator angle in relation to the instantaneous angle of the outboard motor.

3.3 Morphological Matrix

A morphological matrix was made to illustrate the different options that were available to base the concepts on, see Table 3.1. It is built of a column of functions to the left, these are problems that has to be solved. The rows of the matrix represent the means, the possible solutions of these problems.

Table 3.1. Morphological matrix.

Function \ Mean	Mean 1	Mean 2	Mean 3	Mean 4
Boat Motors	Trolling motor 12V	Trolling motor 24V	Custom Built	Small RC motor
Accumulator	LiFePo	AGM Deep Cycle	Custom Lithium Pack	
Control Motors	Servo-motors	Stepper-motors		
Localization	GPS	GNSS		
Localization Correction	RTK	Differential GNSS	None	
Heading	IMU	Magnetometer	From Localization	
Dock Detection	Markers on Dock	Surface Detection	Waypoints	Neural Network
Obstacle Detection	Neural Network	Template Matching		
Obstacle ranging	LiDAR	Stereo Vision	Radar	
Drive-By-Wire	Gear-Belt Pulley	Direct Drive	Linear Actuator	Pre-Built Solution
Near Field	Ultrasonic Sensors	Short Range Radar	Infrared Sensors	LiDAR
Dock Contact	Load Cells	Binary Switch	None	
Legend:	**Concept 1**	**Concept 2**	**Concept 3**	

Three different concepts where deduced from the matrix each with their own distinct colour. The three concepts, *Concept 1, 2 and 3* will be discussed in detail in the following text.

3.4 Concept 1: Markers on Dock

This concept represents what the team calls a ”lean sensor approach” due to its relatively low cost. It is defined by having a less accurate GPS system which introduces the need for another way of accurately determining the position of the dock. In this case, it is solved with AprilTag markers on the dock.

3.4.1 Drivetrain

The thrust motors in this concept would be custom designed for this particular application and incorporate a BLDC motor submerged in a sealed propeller enclosure (similar to the azimuth and trolling motor examples in Section 2.3 . This may be a good solution for saving money while still achieving a system with the desired performance. It would however take a considerable amount of time to design and assemble. Also, there are limitations in what is feasible to fabricate and there is a risk that the motors may get damaged by moisture if not designed and built properly. The batteries to drive these motors are deep cycle AGM batteries. The AGM batteries provide a cheap but heavy solution. The weight and cycling capabilities of these may effect overall system robustness and expandability poorly, but would most likely be negligible compared to other aspects.

This concept includes the ”direct” drive-by-wire solution that was discussed in more depth in Section 3.2.1. The direct drive layout provides a cheaper and easier to implement solution since there is less components required in comparison to the other layouts. With that being said, there is less versatility in gearing the system for more torque/speed as required. Because of this there is a risk that the system won’t be able to respond as fast as necessary for a safe and effective steering system. It is also harder to find hollow bore stepper motors (especially those that are waterproof and include encoders), so sourcing options are quite limited.

3.4.2 Positioning

The general idea of this concept in terms of positioning is to utilize the bare minimum when it comes to GPS without any accuracy increasing correction techniques. Instead, more reliance is put into the readings from the IMU. Correction and accuracy is held up through data morphing and estimation using KF. This would reduce costs though would increase the workload in terms of implementation, validation and verification.

3.4.3 Obstacle Detection

The lower accuracy GPS utilized in this concept makes it unfeasible to use GPS to guide the boat all the way in to the dock. A new function needs to be added in order to position the boat in to the right spot, this is done with markers on the dock, more specifically AprilTags, see Figure 3.5. The AprilTags are recessed in to the docks rubber front to protect them from damage. The AprilTags with the right software give quite an accurate distance and angle to the dock guiding the boat in from ca 25 meters until the near field sensors can take over at around 2-4 meters.

The obstacle detection is handled by a neural net running on an embedded computer. When an object is found, the positioning of that object relative to the boat is handled by a stereo vision camera. It has a range of approximately 20 meters which should be sufficient to be able to avoid a collision because of the vessels proposed speed and stopping ability. An IR stereo vision camera was also considered. The IR could add benefits for operating the vessel in dark conditions. According to the simplified scope, the vessel will be operating in well lit environments and have the possibility for artificial lighting, an IR stereo camera system was therefore disregarded.

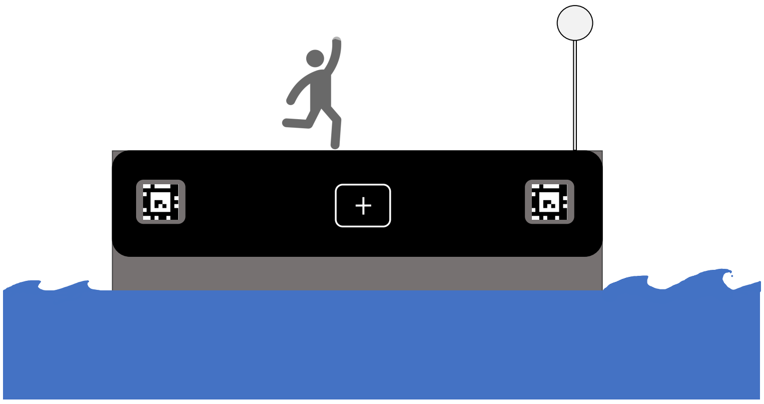

Figure 3.5. Dock with AprilTag modification.

3.4.4 Near Field

For this concept, two ultrasonic sensors at the front of the boat is used for the near-dock approach as they provide good accuracy and robustness at a low cost. This configuration can be seen in Figure 3.6. The change in distance during the dock approach could be used to control the motors to ensure a low impact speed. The distance difference between the two sensors could together with trigonometrical calculations be used to decide the heading angle to the dock, but scattering of ultrasonic waves may be a problem. As for ensuring contact to the dock, the thought is to utilize the same ultrasonic sensors by assuming contact when the distance to the dock reaches zero. To keep it positioned to the dock, the motors could be controlled if the distance starts to deviate from zero. Additional ultrasonic sensors could be placed around the boat hull for basic hazard detection. To work in different ambient conditions, IP67-certified sensors with additional cover for debris could be used.

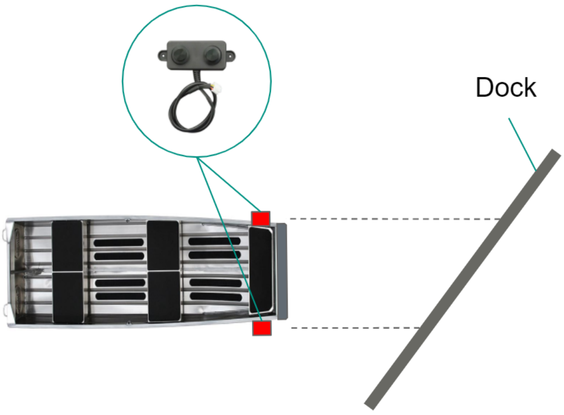

Figure 3.6. Ultrasonic sensor configuration for the near-dock approach.

3.5 Concept 2: Waypoint with Stereo Camera

This concept is defined by its use of accurate GPS-positioning eliminating the need for markers on the dock. It uses a stereo vision system for object detection and avoidance.

3.5.1 Drivetrain

Two commercial 12V trolling motors that each produce approximately 220 Newton of thrust are used in this concept. Although this may not be the best performing option, it strikes a good balance between cost, ease of implementation, and hazard avoidance robustness. It is hard to quantify exactly how well the vessel will maneuver this early in the design phase, but early conservative estimates show that these motors should provide sufficient power to meet the technical requirements and respond fast enough to potential hazards. The batteries in this concept are the same as *Concept 1* (AGM deep cycle). Again, not the best performing option, but they provide a balanced solution in regards to cost and performance.

The geared belt pulley is used in this concept's drive-by-wire system. This solution is discussed in detail in Section 3.2.2. It may be more complex than the direct drive system in *Concept 1*, but the performance, versatility, and expandibility are greatly improved. Having the ability to gear up/down the stepper motor allows us to tune the system performance based on testing data. Also, using standard stepper motors means more options are available for selection.

3.5.2 Positioning

This concept uses high accuracy GNSS together with the correction technology Network RTK from SWEPOS. SWEPOS provides a Machine-to-Machine (M2M) Sim

Card for internet connection, to enable usage of NTRIP, and have base stations located around Stockholm, as seen in Figure 3.7. This results in positioning with high accuracy, i.e. an error as little as 30 mm since we are close enough to their base stations, and would be increasing the reliability of the system. Due to this increase in positional accuracy, heading can be determined together with an magnetometer. Though this somewhat would increase the cost of the system, it increases the reliability and eases the implementation.

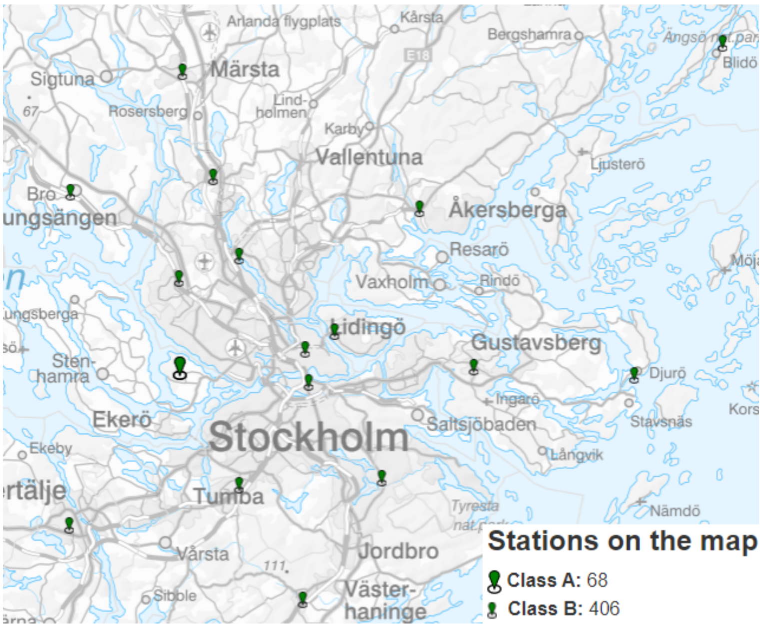

Figure 3.7. A map over SWEPOS Base Stations in Stockholm [37].

3.5.3 Obstacle Detection

Because of the increase in GPS accuracy the need for an additional function to guide the boat in to the dock is not necessary. The boat will be able to be guided in to a predefined waypoint very accurately. The object detection will, just as in *Concept 1*, be handled with a neural network running on an embedded computer and the object localization will be achieved with a stereo camera system.

3.5.4 Near Field

This concept uses the same configuration of the ultrasonic sensors as presented in Section 3.4.4 for the near-dock approach and control of boat impact speed. The difference lies in the dock contact where this concept would use two compression load cells beneath the front bumper to ensure that the boat is in contact with the dock, see configuration in Figure 3.8. When in contact, the force measurements would be used to control the motors to provide enough thrust to keep the boat in contact with the dock during the entire boarding/disembarkation process. Just as in *Concept 1*, additional ultrasonic sensors would be placed around the boat hull for basic hazard detection.

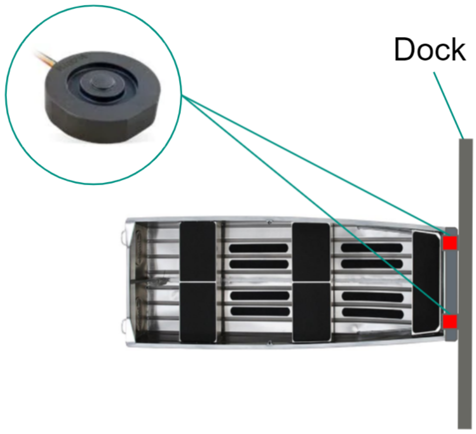

Figure 3.8. Load cell configuration for keeping dock contact.

3.6 Concept 3: Waypoint with LiDAR

This concept relies, just like *Concept 2*, on high accuracy GPS to guide it in to the right position on the dock. Instead of a stereo vision system, it utilizes a LiDAR sensor to determine a detected objects position and the near field ranging is handled by a radar system. The drivetrain consists of a high performance 24V configuration.

3.6.1 Drivetrain

The drivetrain in this concept has the same drive-by-wire system as *Concept 2*, but incorporates powerful 24V motors with approximately 350 Newtons of thrust each. The 24V motors provide a a better preforming system that can respond better to its environment, but is considerably more expensive. The motors themselves cost twice as much as their 12V counterparts and the system then requires twice as many batteries to meet the demands of these motors too. In addition, this concept utilizes LiFeP04 batteries which are better performing than AGM, but also cost nearly 4x as much. Although this is the more ideal system, it is most likely too expensive for our given budget.

3.6.2 Positioning

Concept 3 utilizes the same positioning system as *Concept 2*, see Section 3.5.2.

3.6.3 Obstacle Detection

Concept 3 is similar to *Concept 2* in that that it uses high precision GPS that eliminates the need for other localization techniques like markers on the dock. It uses a single camera that is used for object detection with a neural network. For object localization the concept uses a LiDAR system.

There are several LiDAR options on the market. One high-end 3D LiDAR is the Robosense RS-LIDAR-16. Although not being the most expensive LiDAR, the RS-LIDAR-16 still costs about 35 000 kr [55] [70]. This is significantly out of budget for this project. On the cheaper end we have the Livox Mid-40. With the sacrifice of the FOV the Mid-40 becomes a lot cheaper at around 5000 kr [46]. While the accuracy and range of the LiDAR system is very appealing, it does require more work in implementation and testing; especially in the fusion of the LiDAR system and the vision system used for object detection.

Figure 3.9. Robosense RS-16 to the left and Livox Mid 40 to the right [70] [47].

3.6.4 Near Field

The near-dock approach for this concept is solved with mmWave radar and this configuration can be seen in Figure 3.10. This option provides better environmental robustness as opposed to the ultrasonic sensors. It also provides three outputs of interest in forms of range, velocity and angle in one single reading. As it performs in a greater range than the ultrasonic sensors, additional radar units could be placed around the boat hull to deliver more advanced hazard detection. The radar option comes at a higher cost than the ultrasonic option and could be more challenging to implement correctly. This concept would utilize the same load cell configuration as presented in Section 3.5.4 to ensure dock contact during the boarding/disembarkation process.

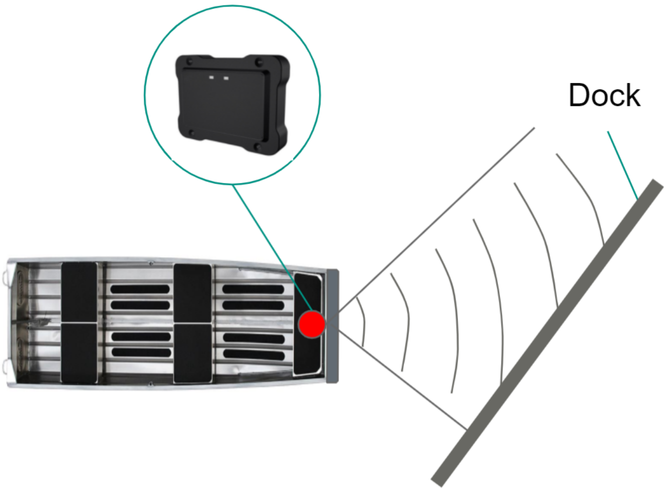

Figure 3.10. Radar configuration for the near-dock approach.

3.7 Evaluation

With all the pros and cons in mind for each concept generated, the group made a final evaluation with help of a weighted decision matrix, see Table 3.2. This gave the opportunity to go through all the important criteria of the system in a structured way. Points were given to the different concepts in a range of 0-2, with 0 being the worst an 2 the best. The evaluation criteria were weighted in terms of importance, with 5 being the highest and 1 the lowest. The points for each criteria were multiplied with the weight for a combined score in each category. The scores were then summed to a total score for each concept.

Table 3.2. Weighted decision matrix.

Criteria		Concepts		
	Weight [1-5]	Concept 1	Concept 2	Concept 3
Ease of implementation	5	1	2	1
Purchase cost	4	2	1	0
Future running costs	1	2	0	0
Docking accuracy	4	0	2	2
Lighting robustness	2	0	1	2
Hazard avoidance	3	1	1	1
Weather robustness	2	0	1	1
Future Expandability	3	1	2	2
Avoiding dock modification	3	0	2	2
Total		21	41	34

The winning concept turned out to be the one named ***Concept 2***. The concept represents a balanced approach, with good scores in the important categories of ease of implementation, cost and docking accuracy. The group agreed that *Concept 2* is the most promising concept and that it would be the concept to continue work on in this project.

3.8 Final Concept

The final concept is based on *Concept 2*, see the morphological matrix in Table 3.1 and the detailed description in Section 3.5 for full details. A sketch was developed to illustrate how the prototype will look with all components and strategies outlined in the concept description, see Figure 3.11.

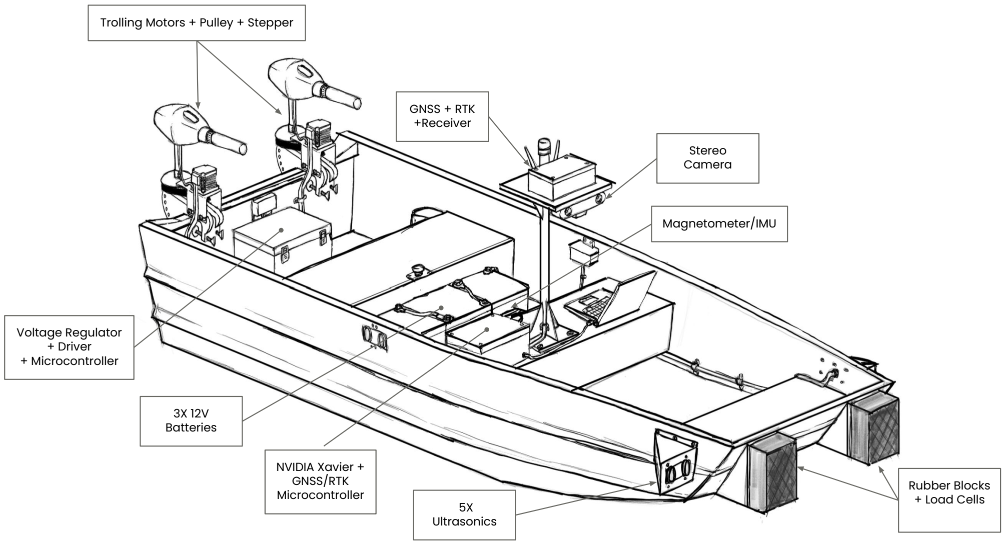

Figure 3.11. Sketch of the final concept.

The weight of the whole system is estimated at approximately 315 kg, with everything considered, and should reach a top speed of around 8 kph. The main contributor to the weight is three AGM batteries. Three 100 Ah batteries are necessary to sufficiently power the two outboard motors for approximately 4 hours testing. Each subsystem does its own computations on separate micro controllers to preserve the ability of independent testing/development and improve diagnostics. Communications between the integrated systems are done via CAN-bus protocol to ensure portability with Candela's existing vessels.

The docking approach for the concept can be split in to four stages:

1. **Approach and avoidance**: At 50 meters from the docking position, an operator activates the AutoDocking protocol. The precision GNSS system coupled with path planning software guides the boat towards the dock. The obstacle detection system is active to avoid hazards or completely abort the approach if need be. It remains active throughout the docking sequence.

2. **Dock impact**: At approximately 3-4 meters, the ultrasonic sensors detects the dock and makes sure that the impact to the dock is at a safe and comfortable speed.

3. **Stationary at dock**: The force sensors makes sure that the boat is stationary as it it pressing up against the dock.

4. **Leaving the dock**: At a given signal, the boat backs out perpendicularly to the dock to a predefined distance. It then turns around and starts heading to its next destination.

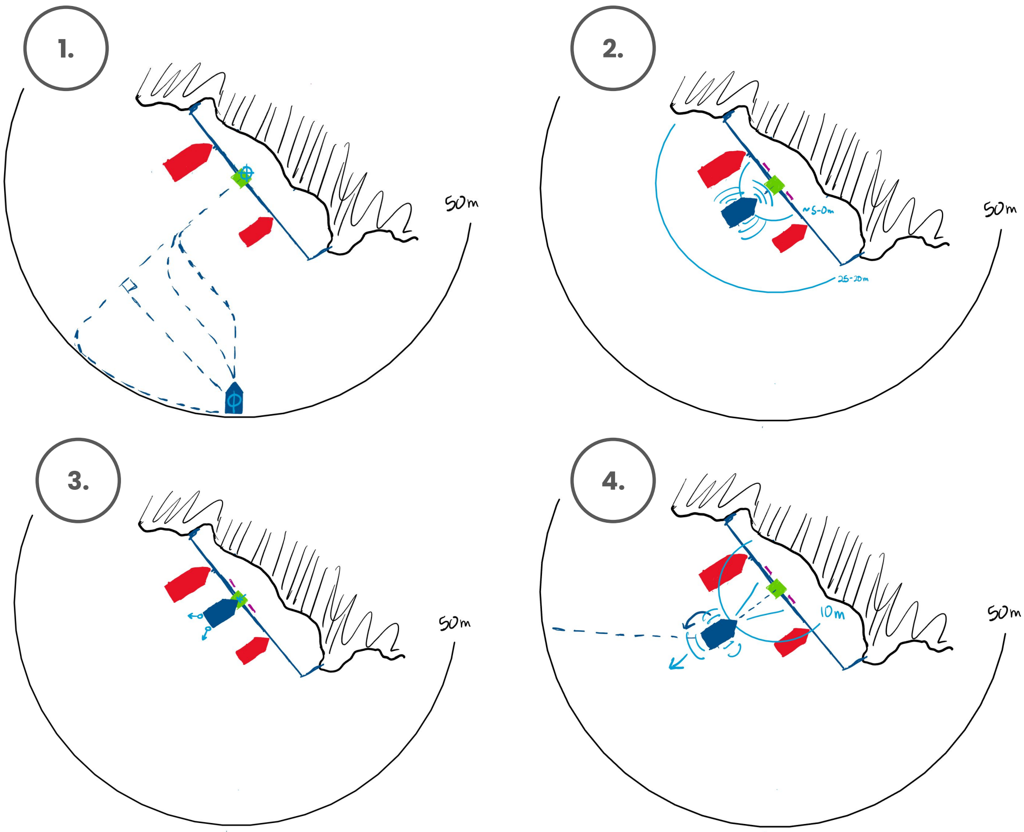

Figure 3.12. The four stages of the docking procedure.

Chapter 4

Future work

4.1 BOM and Purchasing

At the time of this report's conception, several of the specific key items have been chosen. These include many of the most expensive components and those critical to the build schedule starting in September, such as the boat hull, outboard motors, and processors for object detection and GNSS+RTK. A more detailed list of these items can be found in the Bill of Materials (BOM) located in Appendix B and should be on order in the near future. A more detailed BOM is utilized for team use but was excluded from the report due to its large format. These items amounted to roughly 43,000 kr (excluding tax).

A more complete BOM will be developed and additional orders will be placed during the summer months. Items will be continually added to the BOM and purchased until final testing of the fully integrated prototype.

4.2 Autumn 2021 and Forward

Some design work and purchasing may be done over the summer months, but this will be at the discretion of individual members and not required. For the most part, project activity will not resume until the start of the Autumn semester (beginning of September). A detailed preliminary schedule starting in September is shown by the Gantt chart located in Appendix A. Monday.com provided the online Gantt interface to develop the Team's schedule [58].

Due to the large and highly integrated scope of this project, significant time spent testing will be required. For this reason, the schedule was built around the "wet" testing start date (when the full system begins testing in the water) required to ensure sufficient time for tuning the system. The team will have roughly 1.5 months of testing if this activity sprint begins in November; this should be sufficient for dialing in the full prototype and ensuring that its meets technical requirements.

In preparation for this sprint, subsystems will do their detailed design and prototyping as soon as the Autumn semester starts. Soon after, each subsystem is expected to test their system performance, tune their software, and then work on integrating their system into the complete system architecture.

4.3 Risk Analysis

To be well prepared for the autumn, a risk analysis was made. The potential risks were identified. These risks were then paired with their probability of occurrence, their impact and the response that should be taken. As seen in Table 4.2 the risks were given a probability from 0-5 and a impact from 1-4. The risks were then placed in a Risk Matrix (Table 4.1) with regards to their impact and probability. The matrix helps visualize which risks the team needs to be extra careful with. The risk level is depicted with the color coding. Red being very high, orange high, yellow low and blue eliminated.

Table 4.1. Risk Analysis Matrix.

		Impact			
		Negligible = 1	Marginal = 2	Critical = 3	Catastrophic = 4
Probability	Certain = 5				
	Likely = 4			#1	
	Possible = 3		#6, #7	#8	
	Unlikely = 2			#2,#4	#9
	Rare = 1	#3			#5
	Eliminate = 0				

Table 4.2. Risk Analysis.

Type	ID	Risk	Probability	Impact	Response
Internal	#1	Other courses/-work takes up more time	4	3	Try to prevent with a good plan and communication. Make sure other teammates can cover up for team members with high workload
Internal	#2	The workload might grow out of hand	2	3	Stay within the scope. Scale it down and make sure we focus on the scope we have defined
Internal	#3	Candela cannot lend sensors	1	1	Buy our own sensors. Try to borrow from KTH.
Internal	#4	Subsystem being bottlenecks	2	3	Plan ahead and make sure focus is on bottleneck tasks
External	#5	No access to Brunnsviken for testing	1	4	Have another place as back up for testing.
External	#6	Bad weather conditions	3	2	Try to get the boat in the water as soon as possible. Plan with the weather forecast . Alternatively find an indoors pool as a back up.
External	#7	Delivery delays	3	2	Be flexible with the plan and work on what is possible without the delayed components.
External	#8	Components are damaged	3	3	Order new components
External	#9	Covid-19 No access to school workshop	2	4	Find another workshop. Candela might be able to lend us space

The risks which of the team needs to be extra careful with are the impact of other courses/work, Covid-19 affecting the workflow and components being damaged. By having a good plan, good communication and showing teammates solidarity the impact of external workload will be closely watched. In case of covid-19 limiting the access to the KTH workshop the team will have backup location were a workshop could be setup. As for components getting damaged the solution will be to have backups at hand for the cheaper components and order new ones as soon as something breaks.

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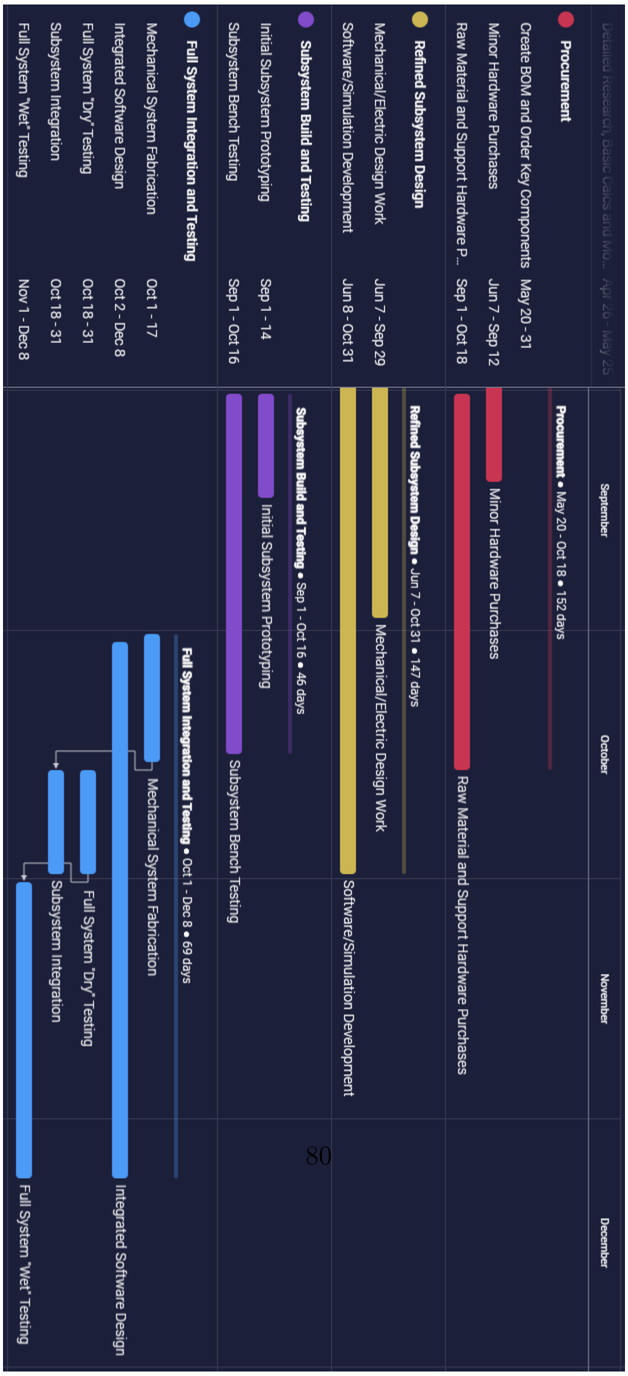
Appendix A

GANTT-Chart



Appendix B

Bill of Materials

ID	Subsystem	Part	Supplier	Notes	Quantity	Price EA [kr]	Price Total [kr]	Ordered (Y/N)
1	Obstacle Detection	Zed 2	Stereo Labs		1	3747	3747	N
2	Obstacle Detection	Nvidia Jetson Xavier NX	Elfa		1	4869	4869	N
3	Drivetrain	Angler 330 Wide	Båtmagneten		1	14320	14320	N
4	Drivetrain	Minn Kota Endura Max 55 36"	SS Marin & Bilbehör		2	4152	8304	N
5	Drivetrain	100 Ah AGM Battery	Amazon		3	1300	3900	N
6	Drivetrain	12V/20A 3-bank Charger	Amazon		1	1423	1423	N
7	Control & Position	U-Blox C099-F9P-2	Digi-Key		1	2074	2074	Y
8	Control & Position	SparkFun HMC6344 Breakout	SparkFun		1	1500	1500	N
9	Control & Position	SparkFun RedBoard Qwiic	SparkFun		1	200	200	N
10	Control & Position	STM32H747I-DISCO	DigiKey		1	900	900	N
11	Near Field	Load Cell FX293X-100A-0100-L	Mouser		2	240	480	N
12	Near Field	Ultrasonic sensor DFR A02YYUW	Mouser		5	165	825	N
13	Near Field	Teensy 3.6 ARM Microcontroller	Mouser		1	330	330	N
14	Near Field	Rubber Block	Viktobult		4	120	480	N
						TOTAL:	43352	

Figure B.1. Bill of Materials