# Bachelor of Science Thesis

## The Platform and Overall Design of an Actively Stabilised, Manoeuvrable Buoy for Offshore Wind Assessment

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TU Delft Delft University of Technology

Challenge the future

# BACHELOR OF SCIENCE THESIS

## THE PLATFORM AND OVERALL DESIGN OF AN ACTIVELY STABILISED, MANOEUVRABLE BUOY FOR OFFSHORE WIND ASSESSMENT

by

**M.H.G. Baas**
**A. Pannekoek**

in partial fulfillment of the requirements for the degree of

**Bachelor of Science**

in Electrical Engineering

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TU Delft Delft University of Technology

# PREFACE

This thesis is the final project that concludes the Electrical Engineering Bachelor's Degree, at the Delft University of Technology. For this project a team of six students has been set out to design, build and test a prototype, within two months' time. The main objective is to test the knowledge and skills of the students obtained in previous years.

The thesis will be defended in a closed session. Here the students will present their findings and answer questions of a thesis committee. The members of the thesis committee are: Prof. Ir. Van der Sluis, Ir. Navalkar and Dr. Cotofana, all connected to the Delft University of Technology. The project is concluded with a public poster presentation.

We would like to express our gratitude to Sachin Navalkar, for his commitment to our project. His patience and helpful guidance have been invaluable. We also want to thank Kees Slinkman, for his practical assistance. Furthermore we want to thank Jan-Willem van Wingerden, for assigning us with a budget. It really had a personal touch to it. We also want to thank Ampelmann Operations B.V. for sharing their knowledge and both the Delft Centre of Systems & Control and the Ship Hydromechanic Towing Tank Laboratory for giving us access to their lab facilities. Adittionally we want to thank Decosier BV, who sponsored the project by making free raw materials available. Finally we want to thank Stephan Groot and Ingrid van Boxel, for reading our thesis and sharing their insights.

*M.H.G. Baas*
*A. Pannekoek*
*Delft, June, 2014*

# Contents

# EXECUTIVE SUMMARY

It is estimated that in the EU, energy consumption will rise to 4,350 TWh in 2030. Offshore wind farms can provide a solution. The technical wind energy potential for offshore wind farms of the European waters is estimated to be 30,000 TWh annually. For feasibility studies, building and operating offshore wind farms weather assessments are needed. These assessments used to be performed by expensive static weather stations. Nowadays advanced buoys are also used. An example is the SEAWATCH Wind LiDaR buoy equipped with a ZephIR300 LiDaR, that performs wind estimations based on the back scatter of laser pulses. Buoys are financially much more attractive than static stations, however they still have two main disadvantages: first, measurements are influenced largely by the pitch and roll motions that are created by sea waves. Second, the buoys need to be moved manually.

The goal of this project is to design a scaled prototype of the SEAWATCH Wind LiDaR buoy, equipped with an actively stabilised platform and autonomous position control. This thesis focuses on the design of the actively stabilised platform and overall design of the prototype. The platform is designed with two gyroscopes, which are used to measure the angle that needs to be compensated. The compensation for motion takes place through three linear electric actuators which are controlled with a microcontroller. The total buoy is designed to closely match the dimensions of the SEAWATCH Wind LiDaR buoy.

After testing the design, it can be concluded that the built prototype can stabilise a maximum angle of 38° within 3,2 s. When stabilised, the maximum deviation angle of the platform is 3,3°. The overall design of the buoy closely matched the scaled dimensions of the SEAWATCH Wind LiDaR buoy. The design is waterproof, floats and is able to sail in desired directions. It is therefore determined that proof of principle for an actively stabilised platform on an offshore buoy is demonstrated.

For further development it is recommended to have a larger budget in order to purchase faster actuators. Also the actuators must be able to resist a large amount of side stress to prevent breakage. It is also recommended to reduce the noise influences of the gyroscope and develop a more accurate test setup. Finally it is recommended to design both a self-sufficient power system and to add partial heave control to the platform control.

# 1

# INTRODUCTION

This chapter presents the introduction of this bachelor thesis. In section 1.1 the background for the project is stated. In section 1.2 the theoretical background of the buoy that needs to be designed is discussed. Also active stabilisation, autonomous position control and the similar products that exist are discussed in section 1.2. In section 1.3 the statement of the problem is described. This statement of the problem leads to the goal and objectives which are discussed respectively in section 1.4 and section 1.5. In the last section, section 1.6, the outline of the thesis is described.

## 1.1. BACKGROUND

We live in a world with a growing energy demand. Meanwhile energy sources like fossil fuels are running out. In order to supply sufficient energy, there is a growing market for renewable energy [1]. Wind power is one such source of renewable energy. Wind energy is converted to electrical power by turbines. These turbines are mostly grouped together in so called wind farms for increased cost efficiency. These wind farms may contain up to several tens of square miles. On land these wind farms compete for space with other purposes like agriculture. It is however also possible to create wind farms offshore. It is estimated that wind resources close to coastal areas have huge energy production potential. The European Environment Agency (EEA) estimates the technical potential of offshore wind energy in the EU alone to be 30,000 TWh annually, which compares favourably with the estimated energy consumption of the EU in 2030 of approximately 4,350 TWh [2]. In short, offshore wind energy has a lot of potential.

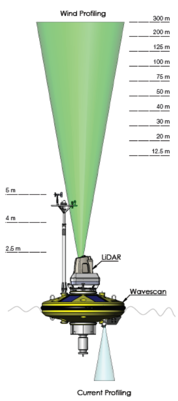


Figure 1.1: Schematic Outlay SEAWATCH Buoy

One of the big challenges of building offshore wind farms is the weather. Since atmospheric and oceanic flow patterns are still largely unknown, the lack of data drives up the costs for design and maintenance, thereby making the investment of building offshore wind resources even more costly and less economically viable. The traditional method for offshore wind assessment involves the use of meteorological masts (met masts). These masts are mostly fixed and can easily cost more than ten million dollars per installation [3]. The latest alternative for these met masts are LiDaR buoys, for instance the SEAWATCH Wind LiDaR buoy, see figure 1.1. This buoy represents the next generation of multipurpose buoys tailored for the renewable energy industry. The buoy accurately measures the speed and direction of wind across the diameter of wind turbine rotors. For this measurement the SEAWATCH Wind LiDaR buoy is equipped with a ZephIR300 LiDaR. This is a system that uses LiDaR, a technology where a laser shoots pulses into the atmosphere and estimates the wind flow based on back scatter of the laser. These SEAWATCH buoys are less expensive than met masts and can be used at more than one location [4].

However, the SEAWATCH buoy as it is, is still a static floating structure with no stabilisation. Hence the measurement of the laser is influenced to a large extent by the pitch and roll of the buoy with the motion of the sea waves. This problem can be addressed with post processing, but that doesn't account for all errors [5]. An improvement of the SEAWATCH buoy to a remote controlled manoeuvrable and actively stabilised structure would have a large impact on wind resource assessments. That is why a group of six Electrical Engineering bachelor students adopted this project as their bachelor thesis to provide a proof of principle.

## 1.2. STATE OF THE ART ANALYSIS

In this section a state of the art analysis has been conducted. The theoretical background of active stabilisation and autonomous position control are addressed in respectively subsection 1.2.1 and subsection 1.2.2. After that, in subsection 1.2.3, the SEAWATCH buoy is discussed. To see what has been done in the field of offshore wind assessment buoys, similar products are discussed as well as their properties in section 1.2.4.

### 1.2.1. ACTIVE STABILISATION

In this subsection the theoretical background of active stabilisation is featured. For this, first a definition is given about the motion of an object. Then the different kinds of sensors to measure this motion are discussed, as well as the active actuators which can be used to compensate this motion.

Actively stabilisation can be defined as the compensation of movement. To stabilise an object the motion must be defined. In order to do that, 'degrees of freedom' (DOF) can be used. This is the number of parameters that determine the state of a physical system. For instance, if an object is considered to be a rigid body in space (a solid object that does not deform), its position can be defined using three translation components and three rotations components [6]. These components can be seen in figure 1.2 and are defined as stated in table 1.1.

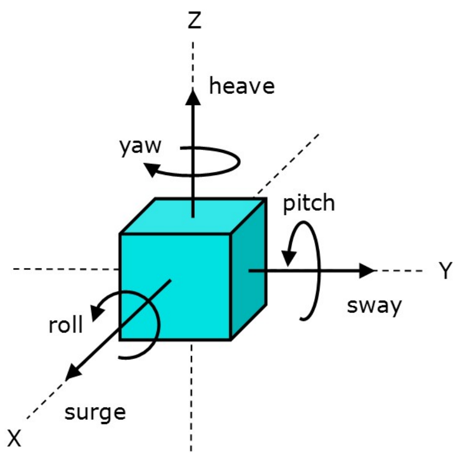



Figure 1.2: Degrees of Freedom Shown on a Rigid Body in Space

| Axis | Translation | Rotation |
|---|---|---|
| X | Surging (forward and backward) | Rolling |
| Y | Swaying (left and right) | Pitching |
| Z | Heaving (up and down) | Yawning |

Table 1.1: The Translation and Rotation Components of a Rigid Body in Space

From this can be concluded that a rigid body in space has six degrees of freedom. However, when the body is fixed on a frame with joints or links, this would remove degrees of freedom and reduce mobility. In accordance with Grodzinski and M'Ewen the degrees of freedom in a mechanism can be calculated from the number of links, the number of joints and the freedoms within the joints [7]. See equation 1.1, where:

$$F = 6(n-1) - \sum_{1}^{g} 6 - f \tag{1.1}$$

- $F$ = resulting degrees of freedom in the system
- $f$ = number of degrees of freedom of the joints
- $n$ = number of links
- $g$ = number of joints

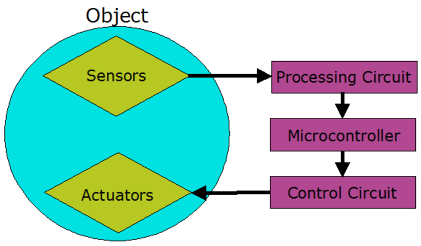



Figure 1.3: Flowchart Stabilisation System

Measurement of the six degrees of freedom, or the motion of an object, is accomplished through sensors that transmit positional and angular data to a processing unit. For stabilisation, this data can be used to control actuators such as is demonstrated in the flowchart of figure 1.3.

There are multiple kinds of sensors and actuators which can be used for a stabilisation system. The most common sensors used for detecting positional and angular data are stated below. Also the various kinds of linear actuators to stabilise a platform are discussed.

### SENSORS

**Inclinometer**
An inclinometer measures the absolute orientation angle around one axis with respect to gravity. It can be used for both vertical as horizontal angle measurement. Inclinometers are typically used for detecting zones of movement, checking deformations like ground movement for buildings and verifying stability for example in dams [8].

**Accelerometer**
An accelerometer measures the acceleration along one axis. Together with the weight of an object the rotation and translation can be deduced. Accelerometers are typically used for measuring the acceleration of vehicles or measuring vibrations [8].

**Gyroscope**
A gyroscope measures the rotational change of orientation around one axis. Because gyroscopes only measure change and not the absolute orientation it is necessary to keep track of change and errors that may occur. Gyroscopes are mostly used for compasses and measuring the rotation of objects. For example aircrafts [8].

### LINEAR ACTUATORS

**Hydraulic actuators**
Hydraulic actuators utilise the power of a liquid or gas flow to transfer power from an electrical input to a mechanical variable, such as speed. Hydraulic actuators transfer this power through relatively high pressures (up to 420 bar) and relatively low flow velocities. Hydraulic actuators are known for their ability to produces large forces. Applications that are most common are manufacturing systems and gas and steam turbine control [9].

**Pneumatic actuators**
Pneumatic actuators utilise the same principles as hydraulic actuators, but far lower pressures are used

(6 to 10 bar). Because far lower pressures are used the flow velocity can be, for the same power, far greater than with a system with high pressures. Pneumatic actuators are most notable being used in combustible engines, but also for air compressors, pumps, switches and countless other industrial purposes [9].

**Electric actuators**

Linear electric actuators convert the rotary motion of an electric motor into a linear motion, for instance the motion created by a servo. Translating the motion can both be done with a screw technique and a wheel and axle technique. Electric actuators are mostly used for motion control, for example electric chairs [10].

### 1.2.2. AUTONOMOUS POSITION CONTROL

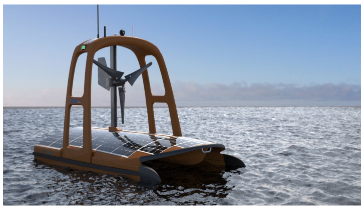


Figure 1.4: The C-Enduro, an Autonomous Surface Vessel, in Action

In this section the background of autonomous position control is briefly explained. There are no commercially available buoys which can autonomous control their position. However unmanned boats exists. These unmanned boats can autonomously navigate to a place and hold their new position. These boats are known as 'Autonomous Surface Vessels' (ASV's). ASV's are used for multiple purposes which include; military, environmental and commercial purposes. The C-Enduro, see figure 1.4 is such an ASV. This vessel is equipped with different sensors and is used for monitoring oceanographic patterns like currents. The C-Enduro is shaped like a catamaran and is 4.2 m long and 2.4 m wide.

Autonomous vessels are mostly powered by diesel fuel cells, which are sometimes accompanied by solar and wind energy. This is also the case with the C-Enduro. Here solar panels and wind turbines are mounted on the deck of the vessel, thereby allowing the boat to cover more than 6000 km during three months.

The positioning system of ASV's generally exist of a central processing unit (CPU), a GPS receiver, an electric compass (gyroscope) and two thrusters which are mounted on the bottom of the vessel. The CPU gets information about its position from the GPS receiver and the gyroscope and translates that to power the thrusters. By varying the amount of power to each thruster, the vessel can be steered and moved to a desired destination. Hence there is no need of a rudder. The CPU of the vessel also receives DGPS signals via telephone communication and sends that to the GPS unit. A DGPS signal contains GPS information of a land station and is used to correct the GPS receiver, making it more accurate. It is smart to use two modes for determining the position and setting a course. One mode is for when the vessel is relatively far away from the set destination and the other is for when it is relatively close. In the far-away-mode the vessel determines the position in large intervals and adjusts its course at the same interval time. This conserves energy consumption of the CPU and GPS unit. In the close-mode the interval time can be less, which allows the vessel to position itself more accurately [11].

### 1.2.3. THE SEAWATCH WIND LIDAR BUOY

Figure 1.5: The SEAWATCH Wind LiDaR Buoy in Action

In this section information about the SEAWATCH Wind LiDaR buoy, see figure 1.5, is provided. This buoy is developed on the basis of the Wavescan buoy, which has been deployed since 1985 with great results in the most hostile oceanographic environments.

As stated before this buoy accurately measures the speed and direction of the wind. This is used to do accurate estimations for wind across the diameter of wind turbine rotors. For this measurements the SEAWATCH buoy uses a ZephIR300 LiDaR. The ZephIR300 LiDaR is based on LiDaR technology, which uses the back-scatter from a laser to measure data. The ZephIR300 LiDaR can measure at ten levels from 12.5 m to 300 m. It measures wind speed from a range of 1 m/s to 70 m/s, with an accuracy of 0.5%. Furthermore the ZephIR300 LiDaR measures wind direction with an accuracy of 0.5°[12]. The buoy also has sensors which provide oceanographic parameters such as ocean waves and current profiles.

Besides full on-board processing for all measured data, the SEAWATCH buoy has a two-way data communication for data transfer and control. The buoy also had a position tracker for increased safety. Furthermore the buoy is modular for easy transport and local assembly.

The buoy as shown in figure 1.5 is made from polyethylene, aluminium and stainless steel. The buoy has a diameter of 2.8 m. The ZephIR300 LiDaR is mounted on top and has a diameter of 1.12 m. A detailed drawing of the ZephIR300 is shown in figure 1.6. The total height of the buoy is 6.1 m. Of which the mast protrudes 3.5 m above sea level. The weight of the buoy with the ZephIR300 LiDaR is approximated at 1200 kg [4].

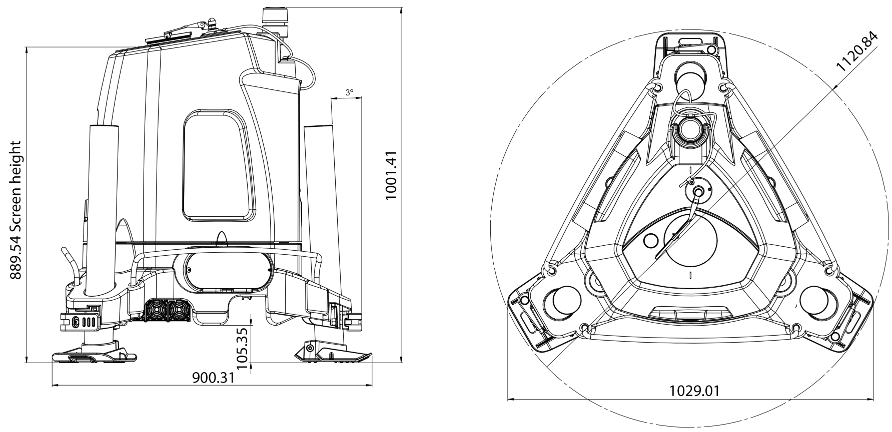



Figure 1.6: Detailed Drawing of the ZephIR300 LiDaR

### 1.2.4. SIMILAR PRODUCTS

The buoy that needs to be designed is a variation on the SEAWATCH buoy. Products similar to that buoy are the Neptune project, the FLiDAR, the Wind Sentinel™ and the Fraunhofer IWES Wind LiDaR Buoy. Besides these buoys there are a couple of other running projects but their progress is negligible in comparison with the previous buoys. In this subsection the properties of all this buoys are discussed and compared.

The Neptune project, see figure 1.7, is a project that is being developed in Barcelona, Spain. The project is financed by KIC InnoEnergy SE. The project originates from the high costs of wind assessment in the Mediterranean Sea. The goal of the project is to provide accurate wind and wave data which can be used in offshore wind assessment as well as in the validation of wind- and oceanographic simulation models. The project uses the ZephIR300 LiDaR. An active mechanical motion compensation frame is under development to make sure that the measurements are accurate [13]. Besides the mechanical compensation a post processing algorithm is under development. The buoy is energy autonomous and provides itself with 120 W via solar and wind energy. The buoy is expected to enter the market in 2015 [14].

Figure 1.7: The Neptune Project Buoy in Action

The FLiDAR, see figure 1.8, is an offshore wind assessment buoy that is designed and marketed by FLiDAR N.V., a joint venture between 3E en OWA (part of the DEME group). The buoy is developed in Belgium. The first prototypes where active at the end of 2011 [15]. The FLiDAR focuses on leasing their buoys as part of a data service agreement. This is been done to minimise risk and maximise flexibility for the customer. The FLiDAR uses the WINDCUBE®v2, which uses LiDaR technology, for its wind measurements. To make sure the measurements are accurate the FLiDAR uses a passive mechanical stabilisation unit in combination with software based measurement correction. The buoy is powered through solar and wind energy and it is autonomous for at least seven days. The FLiDar has been on the market since June 2013 [16].

Figure 1.8: The FLiDAR Buoy in Action

Figure 1.9: The Wind Sentinel Buoy in Action

The WindSentinel™, see figure 1.9, is a wind assessment buoy/vessel that is developed and marketed by AXYS Technologies from Sidney, Canada. The development started in 2008 and in the fall of 2011 the first commercial deployment was carried out. Since 2011 the buoy is deployed all over the world [17]. The WindSentinel™ uses the LiDaR technology based Vindicator®III for its wind measurements. This technology is based on technology developed for the army. Because of the unique way the Vindicator®III measures, it is able to compensate motion errors in the data. The buoy is powered through solar cells and wind turbines, which can support up to 500 W. The buoy is designed for long term deployments. The WindSentinel™ can be remotely monitored for maintenance [18].

Figure 1.10: The Fraunhofer Buoy in Action

The Fraunhofer IWES Wind LiDaR Buoy, see figure 1.10, is developed by Fraunhofer IWES located in Bremerhaven, Germany. The development began in 2011 and the first prototype was launched in the spring of 2013. The Fraunhofer buoy uses the WINDCUBE®v2 LiDaR. It uses no mechanical compensation, but solely relies on post processing data compensation. The buoy relies on wind and solar energy. Once the buoy is deployed it will function under a full service contract including service-, data- and quality control [19]. The second prototype is planned to launch in the first half of 2014. It is unknown when the buoy will enter the market [20].

Each buoy has their own benefits and downsides. To make a proper comparison between each buoy properties are compared in table 1.2. Only one buoy uses active compensation. Most buoys use some kind of post-processing data stabilisation to enhance the results. These approaches treat the problem of errors in the measurements, instead of solving it. The most robust way however is to make sure no errors occur in the first place (treat the disease and not the symptoms). The opportunity lies in actively stabilising the measurement equipment. Besides stabilisation of measurement equipment, the buoys are all moored and need to be manually relocated. This is where another opportunity lies. Costs could be cut immensely if the buoy could autonomously move to its operational area and stay there.

| Property | SEAWATCH | Neptune Project | FLiDAR | Wind Sentinel | Fraunhofer IWES |
|---|---|---|---|---|---|
| On the Market | x | | x | x | |
| Data stabilisation | x | x | x | x | x |
| Active stabilisation | | x | | | |
| Passive stabilisation | | | x | | |
| Autonomously movement | | | | | |
| Moored | x | x | x | x | x |
| Design based on a existing buoy | x | | x | x | |
| Specific Software Tool | | x | | | x |
| Moored buoy | x | x | x | x | x |
| Real Time Communication | x | x | x | x | |
| Wave sensors on board | x | x | | | x |
| Wind Energy Source | | x | x | x | x |
| Solar Energy Source | x | x | x | x | x |

Table 1.2: Property Comparison of Wind Assessment Buoys

## 1.3. STATEMENT OF THE PROBLEM

This section describes the statement of the problem. It will state which issues Delft University of Technology wants a team of six bachelor students to address in a time span of two months and with a small predetermined budget which can be found in appendix A.

The problem at hand can roughly be divided in two. The first problem to be solved is the actively stabilising of the measurement equipment (ZephIR300 LiDaR) aboard of the SEAWATCH buoy when it is offshore in the North Sea. This can be done by an actively stabilised platform, which has little or no tilt with respect to the horizontal axe, such that the measurement errors of the ZephIR300 LiDaR, due to the pitch and roll of sea waves, will no longer occur.

The other problem to be addressed is to equip the SEAWATCH buoy with autonomous position control, such that the buoy can autonomously position itself on a desired set location in the North Sea. This position control needs to be accurate enough to not disturb the measurements of the ZephIR300 LiDaR.

Power supply and wireless communication will not be part of the scope.

## 1.4. GOAL OF THE PROJECT

Based on the assignment described in section 1.1, the research done in section 1.2 and the statement of the problem as stated in section 1.3, the overall goal of the project can be stated as follows:

*Design a scaled prototype of the SEAWATCH Wind LiDaR buoy equipped with: an actively stabilised platform, to account for pitch and roll measurement errors of the ZephIR 300 LiDaR, and autonomous position control, to relocate and account for position drift.*

Because the project is conducted by six students the project is divided in three groups of two students, of which one group will cover the electronics and the design of the prototypes platform controller [21] and another group will cover the remote controlling of the prototype [11]. The last group will cover the design of the stabilised platform and overall prototype. This thesis covers the content of the last mentioned group. All groups will put forth recommendations for the full scale buoy based on their findings. The completion of this goal will be discussed in chapter 6.

## 1.5. OBJECTIVES OF THE THESIS

The objectives of this thesis are derived from the goal. This thesis will focus on the platform and overall design of a scaled prototype, while keeping the design of the full scale buoy in mind. In order to do that the objectives are solely focused on the prototype, but with each design stage the recommendations for the full scale buoy will be presented. The objectives for this thesis are:

1. Design of the actively stabilised platform.
2. Select best suited sensors for delivering input data for the platform controller.
3. Select best suited actuators for transforming output data to the motion of the platform.
4. Design a compact overall lay-out of the working prototype.
5. Build a prototype of the buoy.
6. Acquire test results for proof of principle.

The completion of the objectives will be discussed in chapter 6.

## 1.6. OUTLINE OF THE THESIS

The thesis is drafted from different chapters. Chapter 2 defines the requirements of the project and in chapter 3 the design of the platform is presented. In chapter 4 the overall design of the buoy is finalised with the results of the other two theses included. In chapter 5 the testing of the buoy is discussed and the results are presented. At last, in chapter 6 the conclusions and recommendations are discussed.

# 2

# DESIGN REQUIREMENTS

In the following chapter the requirements for the design of the scaled prototype and the full scale buoy are set. The design of the full scale buoy will be tested through a working scaled prototype. That is why most of the requirements that are set reflect on the prototype. These requirements will be stated in the first part of this chapter. Since there are additional requirements which apply only on the full scale buoy they are discussed separately later on in the chapter.

The prototype and the full scale buoy both have main requirements and additional design requirements. The requirements are categorised as follows:

**Prototype** The main requirements of the prototype can be found in section 2.1 and the design requirements of the prototype in section 2.2.

**Full Scale Buoy** The main requirements of the full scale buoy can be found in section 2.3 and the design requirements of the full scale buoy in section 2.4.

In figure 2.1 a schematic drawing of the buoy is pictured. In the requirements the modules addressed will be highlighted accordingly.

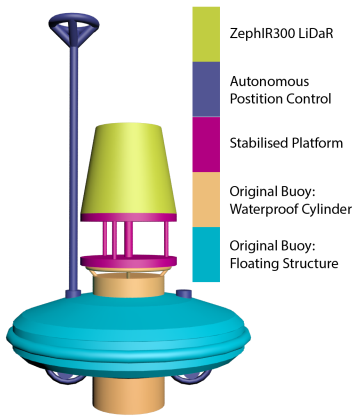



Figure 2.1: Schematic Overview Modified SEAWATCH Buoy

## 2.1. MAIN REQUIREMENTS PROTOTYPE

The main requirements of the prototype follow directly from the objectives. These requirements describe the core of the design. The requirements address the platform that needs to be stabilised, the lay-out of the buoy and the specific requirements set for the building of the prototype.

The focus of the design of the platform is to make sure the ZephIR300 LiDaR can do accurate measurements. For this the platform must remain static with respect to the horizontal. Therefore, the pitch and roll movements of the platform must be compensated. The maximum degree of tilt of the ZephIR300 LiDaR, which allows the ZephIR300 LiDaR to produce accurate and precise measurements is 5°, see figure 2.2. Up to 10° tilt can be compensated with post-processing the data [22]. Since the goal of the project is to compensate for all errors without post-processing correction the maximum allowed degree of tilt is 5°.

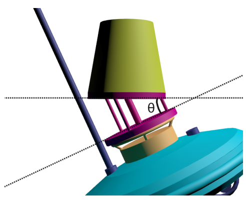



Figure 2.2: The Degree of the Platform that needs to be Compensated.

**2.1.1** *The platform must be able to compensate the pitch and roll movements.*

**2.1.2** *The maximum allowed degree of tilt of the platform is 5° with respect to the horizontal.*

The system must be fast enough to compensate the motion of the platform, so a maximal operating time must be set. The sensors must send their data to the controller, the controller must do their calculations and the actuators must transform the output signal to the desired displacement. The whole process should not take longer than 1 s.

**2.1.3** *The system must have a maximum stabilisation time of 1 s.*

The lay-out of the prototype must be designed. That means that the mechanical parts of the platform, the platform stabilisation controller [21] and the autonomous position controller [11] must be connected in working order and located on the buoy. In order to ensure that the components are arranged as per the schematic, the total package of active components, except the propulsion equipment, must fit in a virtual cylinder with a radius of 10 cm and a height of 30 cm. In figure 2.1 these parts are indicated in orange and fuchsia. The propulsion equipment must be located below the buoy.

**2.1.4** *The lay-out of the active components, except the propulsion equipment, must fit in a virtual cylinder with a radius of 10 cm and a height of 30 cm.*

**2.1.5** *Space below the buoy must be reserved for the propulsion equipment.*

Since the prototype will be scaled with respect to the buoy, a scale needs to be determined. This scale is based on a trade-off between the size of the components and the fact the prototype must be able to be carried by one person. With the trade off in mind the scale is chosen at 1:5.

**2.1.6** *The prototype must be built on a 1:5 scale.*

The project has a time limit and a limited budget. The time limit is the duration of the 'Bachelor Afstudeer Project' and the budget can be found in appendix A. To account for this, some requirements are set.

**2.1.7** *The prototype must be built in two months.*

**2.1.8** *The costs of the prototype must be within budget.*

## 2.2. DESIGN REQUIREMENTS PROTOTYPE

In the following section the specified design requirements for the prototype are stated. Each subsection describes the requirements of that particular part of the prototype. In subsection 2.2.1 the platform requirements are set. In subsection 2.2.2 the buoy design requirements are set and in subsection 2.2.3 the sailing requirements are set. To clarify the subsections the particular parts are highlighted in the accompanying figures.

### 2.2.1. PLATFORM REQUIREMENTS PROTOTYPE

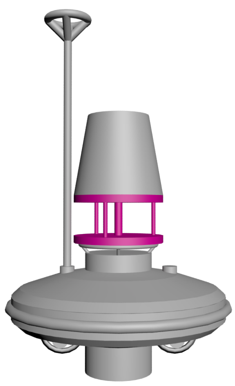


Figure 2.3: Schematic Overview Modified Buoy: The Platform

The platform needs to comply with requirement 2.1.2, requirement 2.1.3 and requirement 2.1.6. Besides the main requirements the platform must also comply with the following requirements:

The platform on the buoy needs to support the ZephIR300 LiDaR. Therefore, the platform must be large enough and strong enough to fit and support the ZephIR300 LiDaR and its fixtures. The prototype platform needs to be able to support the scaled dimensions and weight. For the dimensions see figure 1.6. The original weight is 55 kg. The new dimensions and weight are based upon requirement 2.1.6.

**2.2.1** *The scaled measurements of the ZephIR300 LiDaR and its fixtures must fit on the platform.*

**2.2.2** *The scaled weight of the ZephIR300 LiDaR and its fixtures must be supported by the platform.*

The platform must compensates the angles of the buoy with respect to the horizontal axes, see figure 2.2. Because the platform has physical limitations on the maximum correctable angle a maximum angle to which the buoy must be able to compensate has to be set. The buoy will be designed to operate in the North Sea where frequent maximum wave angles are 37°, see appendix B. Therefore, the maximum compensated degree must be 37°.

**2.2.3** *The maximum allowed degree of the platform that must be compensated is 37°.*

To be able to accurately control the platform of the prototype and manage its exact position, the components must have a specified resolution. The sensors must be able to sense an angle displacement with 90 °/s with a sensitivity of 0.5 °/s. The actuators must be able to control the platform to compensate the 0.5 ° so its accuracy of displacement must be 1 *mm*.

**2.2.4** *The sensors must have a minimum scale of 90 °/s with a sensitivity of 0.5 °/s.*

**2.2.5** *The actuators must have a minimum accuracy of 1 mm.*

The maximum processing time of the compensating platform is 1 s, see 2.1.3. The platform controller consists of a microcontroller which is out of the scope of this thesis. The maximum processing time of the microcontroller is roughly estimated at 1 ms. The sensors are much faster than the actuators, they have a reaction time of 2 ms. Therefore, the actuators will roughly take up 97 % of the processing time. Because the processing time of the actuator depends upon the distance it needs to compensate it is more logical to define a speed than a processing time. The maximum degree that the actuator needs to compensate per second is 28.6 °/s, see appendix B. Therefore, the minimum speed of the actuators is estimated at 30 mm/s.

**2.2.6** *The sensors must have a maximum processing time of 2 ms.*

**2.2.7** *The actuators must have a minimum speed of 30 mm/s.*

### 2.2.2. BUOY DESIGN REQUIREMENTS PROTOTYPE

Part of the prototype is the design of the buoy. Requirement 2.1.4, requirement 2.1.5 and requirement 2.1.6 apply to the design of the buoy. Besides these main requirements multiple design requirements apply. Because the prototype that is being designed is based on the SEAWATCH Wind LiDaR Buoy the prototype must be a close replica of that buoy.

**2.2.8** *The prototype must be a close replica of the SEAWATCH Wind LiDAR Buoy.*

The prototype must demonstrate that a floating buoy can be equipped with a stabilised platform and autonomous position control and navigation. Therefore, the prototype must be able to float and be waterproof.

**2.2.9** *The prototype must be able to float.*

**2.2.10** *All components must be or made waterproof.*

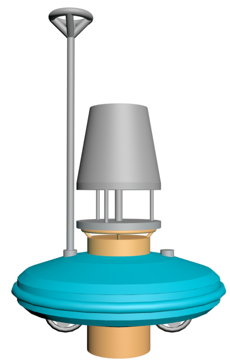


Figure 2.4: Schematic Overview Modified Buoy: The Buoy Design

### 2.2.3. SAILING REQUIREMENTS PROTOTYPE

For the autonomous position control and navigation some requirements are set as well. Although most of the design of the sailing part of the buoy is designed in another thesis [11] some design requirements are part of the overall design of the prototype. The main requirement 2.1.6 applies to the sailing part of the buoy.

The prototype must master the basics of sailing to be able to conquer more difficult manoeuvres like autonomous position control. Therefore, part of the overall design of the buoy is the ability to sail by its own resources.

**2.2.11** *The prototype must be able to sail by its own resources.*

Besides the requirement to sail the prototype will need to have the ability to steer while sailing. Without that ability the prototype will be unable to perform other manoeuvres.

**2.2.12** *The prototype must be able to steer.*

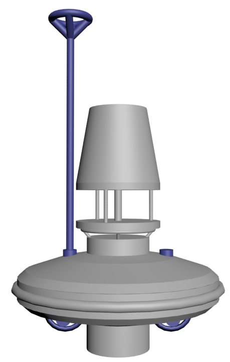


Figure 2.5: Schematic Overview Modified Buoy: Sailing

## 2.3. MAIN REQUIREMENTS FULL SCALE BUOY

The main requirements of the full scale buoy follow from the goal of the project. Therefore, more and broader requirements are set for the full scale buoy than for the prototype. However, the main requirements of the prototype will, to some extent, be valid for the full scale buoy. The main requirements that are valid for the full scale buoy are stated in table 2.1.

| Requirement | Valid for full scale buoy | Modification |
|---|---|---|
| Requirement 2.1.1 | Yes | None |
| Requirement 2.1.2 | Yes | None |
| Requirement 2.1.3 | Yes | Longer period of time |
| Requirement 2.1.4 | Yes | Cylinder with $r = 0.5$ m and $h = 1.5$ m |
| Requirement 2.1.5 | Yes | None |
| Requirement 2.1.6 | No | None |
| Requirement 2.1.7 | No | None |
| Requirement 2.1.8 | No | None |

Table 2.1: Validity Prototype Main Requirements for the Full Scale Buoy

Besides the requirements stated in table 2.1 the full scale buoy has some additional main requirements. The buoy must be able to make wind measurements in the North Sea and be continuously operational for one month. Because of that the buoy must withstand the offshore weather conditions of the North Sea and be able to manage its energy for one month.

**2.3.1** *The buoy must be able to operate in the weather conditions of the North Sea for one month.*

**2.3.2** *The buoy must be able to be self-sufficient in its energy consumption for one month.*

## 2.4. DESIGN REQUIREMENTS FULL SCALE BUOY

The design requirements of the prototype will, to some extent, also be valid for the full scale buoy. The design requirements that are valid for the full scale buoy are stated in table 2.2.

| Requirement | Valid for full scale buoy | Modification |
|---|---|---|
| Requirement 2.2.1 | Yes | Non scaled measurements |
| Requirement 2.2.2 | Yes | Non scaled measurements |
| Requirement 2.2.3 | Yes | None |
| Requirement 2.2.4 | Yes | None |
| Requirement 2.2.5 | Yes | Lower accuracy |
| Requirement 2.2.6 | Yes | None |
| Requirement 2.2.7 | Yes | Longer period of time |
| Requirement 2.2.8 | No | None |
| Requirement 2.2.9 | Yes | None |
| Requirement 2.2.10 | Yes | None |
| Requirement 2.2.11 | Yes | None |
| Requirement 2.2.12 | Yes | None |

Table 2.2: Validity Prototype Design Requirements for the Full Scale Buoy

Besides the requirements of the prototype that are valid for the full scale buoy some additional design requirements are set. These will be discussed in the subsection 2.4.1, subsection 2.4.2, subsection 2.4.3 and subsection 2.4.4.

### 2.4.1. POWER REQUIREMENTS FULL SCALE BUOY

The full scale buoy need to be self-sufficient in its energy consumption for 1 month, see requirement 2.3.2. Therefore, there are restrictions to the energy use of the different components of the buoy.

The original SEAWATCH buoy has a lithium battery bank up to 9792 Ah [$I_{\text{lithium}}$] and a lead-acid battery bank up to 248 Ah [$I_{\text{leadacid}}$], both at 12 V [$U$]. These battery banks can be loaded with solar panels with a total of 180 W [$S$] [4]. Because the buoy will be outfitted with extra equipment and the original capacity wasn't designed for that the capacity of the battery banks is doubled in the new design. Via equation 2.1 the total power needed for the buoy is calculated. The power the new buoy will have at its disposal is roughly 400 W. The existing systems of the buoy consume around 200 W [3]. Therefore, the division of power between the active stabilisation and the autonomous position control is 75 W to 125 W.

$$P = \frac{(2 \times (I_{\text{lithium}} + I_{\text{leadacid}}) \times U) + S \times h \times \eta}{h} = 394W \tag{2.1}$$

with:

- $I_{\text{leadacid}} = 248$ Ah
- $I_{\text{lithium}} = 9792$ Ah
- $U = 12$ V
- $S = 180$ W
- $h = 720$ hours/month
- $\eta = 1/3$ [Fraction of time the solar panel is operational]

**2.4.1** *The maximum energy consumption of the active stabilisation unit is 75 W.*

**2.4.2** *The maximum energy consumption of the autonomous position control unit is 125 W.*

### 2.4.2. FULL SCALE BUOY PRODUCTION REQUIREMENTS

The SEAWATCH Wind LiDaR buoy consists of multiple, separately designed, modules which makes the buoy very reliable. If a component fails, it is easily replaced with minimal downtime. To make sure this property retains its value on the full scale buoy the units must be easily replaceable.

**2.4.3** *The stabilisation and autonomous position control unit must be modular.*

Because the full scale buoy will likely feature more options in the future the units will need to be designed with that in mind. Because of that the designs of the stabilisation and autonomous position control unit must be easily expandable.

**2.4.4** *The designs of the stabilisation and autonomous position control unit must be easily expandable.*

### 2.4.3. FULL SCALE BUOY ECOLOGICAL REQUIREMENTS

Since the full scale buoy will be in an offshore environment with wildlife and other ecological factors the buoy must comply with the European regulations [23].

**2.4.5** *The buoy must comply with the European regulations concerning the environment, recycling and safety.*

A circular business model, which has the intention to recycle the materials that are used, is preferred. With account to this model the components used in the production must be recyclable for roughly 70%.

**2.4.6** *The components used in the production of the buoy must be 70% recyclable.*

### 2.4.4. COMMERCIALLY FOCUSED REQUIREMENTS

The full scale buoy is being developed to be marketed. The project needs to be economically viable. To make sure the costs don't exceed the maximum a rough estimation of the maximum construction cost is made. This estimation is set at € 50.000,-.

**2.4.7** *The construction costs of the full scale buoy may not exceed € 50.000,-.*

# 3

# DESIGN OF THE ACTIVELY STABILISED PLATFORM

This chapter describes the design of the actively stabilised platform. This platform is a component of the prototype of the buoy. The overall design of this buoy will be discussed in chapter 4. The design is done for the case where the ZephIR300 LiDaR needs to be stabilised.

The chapter uses a top down approach. First the topology of the platform will be explained in section 3.1. Then the components which fall within the scope of this thesis will be selected in section 3.2. In section 3.3 will be explained how the components are connected in order to form a stabilising platform. The operation of the platform is explained in section 3.4. Finally, the differences between the platform of the scaled prototype and the full-scale buoy are described in section 3.5.

## 3.1. TOPOLOGY OF THE PLATFORM

In this section the topology of the platform will be addressed. The different kinds of components that are needed to ensure that the platform works are listed here. Also, the placement of the components will be addressed. See also the platform topology in figure 3.1. In the next subsections, the components which fall within the scope of this thesis will be selected.

The platform must satisfy the requirements set in chapter 2. In short: the platform needs to compensate two degrees of freedom, the rotation around the x- and y-axis, known as pitch and roll. See requirement 2.1.1. The platform needs to compensate angles within a range of 5° up to 37°. See also requirements 2.1.2 and 2.2.3. This has to be done within 1 s, requirement 2.1.3. The lay-out of the components of the platform must fit in a virtual cylinder with a radius of 10 cm and a height of 30 cm and built on a scale of 1:5. See requirements 2.1.4 and 2.1.6. Futhermore, the costs of the platform must stay within budget. See requirement 2.1.8 and appendix A.

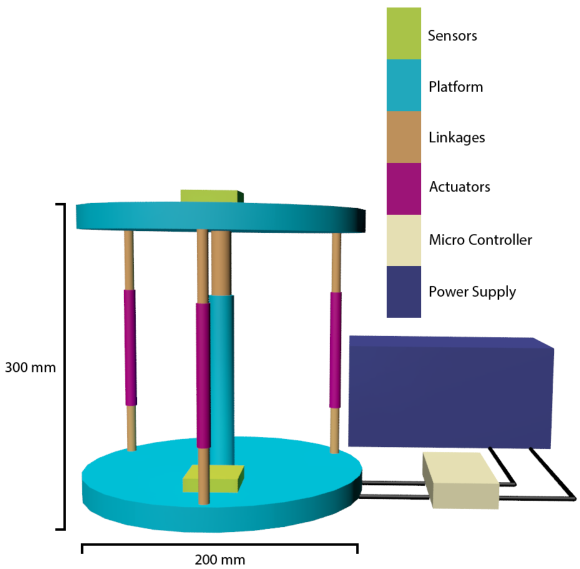


Figure 3.1: Topology of the Actively Stabilised Platform

**Sensors**
In order to measure the angle to be compensated, sensors are needed. In chapter 1, three different kinds of sensors to measure motion are discussed. Because the platform only needs to compensate the pitch and roll movements, accelerometers are not

necessary. Accelerometers only measure translation and not rotation. For rotation both inclinometers and gyroscopes can be used. Gyroscopes measure the angular velocity around an axis. Inclinometers measure the inclination of the object they are mounted on with respect to gravity. In this case it seems applicable to use gyroscopes, because they are providing information about the speed of the motion to be compensated. This can be translated into the angular displacement. Calibrated gyroscopes can be used in pairs to calculate the angle to be compensated. Two gyroscopes are needed for this platform. One on the platform and one on the buoy. See also figure 3.1. In this manner the angle between the platform and the buoy can be determined. In section 3.2.1 the exact gyroscopes will be selected.

**Actuators**
Linear motion compensation is needed and linear actuators are chosen for this purpose. Linear actuators can be controlled to give a variable linear motion. In chapter 1 the different kinds of actuators are discussed. For this scaled prototype linear electric actuators seem the most applicable, because of their properties of easy handling and accuracy.

The platform needs to compensate two degrees of freedom, namely the pitch and roll movement. In this case the use of two, three or four actuators are viable options with a high potential. To make a decision on the number of actuators a multi-criteria analysis has been conducted. This analysis is used for complex decision making. It considers a number of objectives, each with their own weight and looks, to determine which scenario has the most benefit. For this analysis the following facts are considered. The advantage of using two or four actuators is that the control is easy because of orthogonally. With three or four actuators, (partial) heave compensation can be added later. With the use of more actuators, the risks of the platform not working due to a broken actuator decreases, but the price rises. Cost and (partial) heave compensation have the most priority, because this makes the prototype most viable on the market. Reducing the risk of malfunction and the complexity of control are surmountable. This leaves us with the multi-criteria analysis shown in table 3.1. Based on this analysis the scenario with three actuators is the most applicable. In this case the actuators will be distributed equally on the edge of a circle, as can be seen in figure 3.1. In section 3.2.2 the linear actuators will be selected.

| Objective | Weight | Two actuators | Three actuators | Four actuators |
|---|---|---|---|---|
| Complexity of the control | x1 | +2 | -2 | +2 |
| Price | x4 | +2 | +1 | -1 |
| Risk of malfunction | x2 | -3 | +1 | +2 |
| Partial heave compensation | x3 | -3 | +3 | +3 |
| Total benefit | | -5 | +13 | +11 |

Table 3.1: Multi-Criteria Analysis for the Number of Actuators

**Controller**
To transfer the output data of the sensors into useful input data for the actuators, some kind of controller needs to be selected to process data. Most fit for this purpose is a microcontroller. This controller is cheap, small and easy to program. The choice of a microcontroller falls outside the scope of this thesis. A LPC-P1343 microcontroller is chosen [21], [11]. This microcontroller has a clock speed of 12 MHz and communicates through $I^2C$, SPI and UART. Furthermore the microcontroller has 42 in/output pins. This information needs to be considered in the selection of the other components in section 3.2 [24].

**Platform**
The size of the platform must comply with requirements: 2.1.4, 2.1.6 and 2.2.1. This means that the platform needs to be scaled on 1:5 and be able to carry the ZephIR300 LiDaR. The size of the platform has been determined on a radius of 112 mm. This complies exactly with the scaled measurements of the SEAWATCH Wind LiDaR buoys platform.

**Linkages**
The platform needs to be mounted on the three actuators. This must be done in such a way that the platform can move with two degrees of freedom as a result of the linear movement of the actuators. In order to do that the correct linkages need to be selected. This will be done in section 3.2.3. Also a decision has to be made about the number of linkages. The placement of these components can be seen in figure 3.1.

**Power supply**
The design of the power supply falls outside the scope of the project. However the system still needs to be powered to give proof of principle. For the platform, this includes powering the gyroscopes, the three actuators and the microcontroller. In order to do that, a PC power supply is used. A PC power supply can deliver 3,3/5/12 V. These are standard input voltages for components. However this needs to be considered in the choice of components. The PC power supply will be placed outside of the buoy as can be seen in figure 3.1. Here, one has to realise that this option is not available on the full scale buoy.

## 3.2. SELECTING COMPONENTS

In this section the exact components of the platform will be selected. In section 3.2.1 the gyroscopes are chosen. The actuators to be used are selected in section 3.2.2. The linkages will be discussed in 3.2.3.

### 3.2.1. SENSORS

In section 3.1 it is explained that the system will use two gyroscopes as sensors to deliver input data for the microcontroller, which can then be processed into output data for the actuators. In this subsection the choice for a gyroscope is explained.

The gyroscopes must comply with the requirement for the prototype. These requirements are set in chapter 2. The main requirements for the gyroscopes are: 2.1.1, 2.1.8, 2.2.4 and 2.2.6. This roughly means that the gyroscopes must be within budget, measure at least two axes and have the following properties: a maximum processing time of 2 ms and a scale of 90 °\ s with a sensitivity of 0.5 °\ s. Besides these requirements there are also some new demands which follow from selected microcontroller and power supply. These state that the sensors must have a digital output and communicate in $I^2C$ or SPI and have a supply voltage of 3,5/5/12 V.

Three gyroscopes are selected which meet these requirements. This gyroscopes are the MPU-6050 of Inverse [25], the LSM330DLC of STMicroelectronics [26] and the 27911 of Parallax Inc [27]. There properties are shown in table 3.2. Pictures of the gyroscopes are shown in figure 3.2.

| Gyroscope | MPU-6050<br>Inverse | LSM330DLC<br>STMicroelectronics | 27911<br>Parallax Inc |
|---|---|---|---|
| Price | €27.26 | €7.27 | €26.29 |
| Measurement | 3 axis | 3 axis | 3 axis |
| Communication | $I^2C$ and SPI | $I^2C$ and SPI | $I^2C$ and SPI |
| Output | 16 bit | 16 bit | 16 bit |
| Scale/sensitivity | 250 °\ s / 7,6 m°\ s/d<br>500 °\ s / 15,3 m°\ s/d<br>1000 °\ s / 30,5 m°\ s/d<br>2000 °\ s / 61,0 m°\ s/d | 250 °\ s / 8,75 m°\ s/d<br>500 °\ s / 17 m°\ s/d<br>2000 °\ s / 70 m°\ s/d | 250 °\ s / 8,75 m°\ s/d<br>500 °\ s / 17 m°\ s/d<br>2000 °\ s / 70 m°\ s/d |
| Power | 2.5-3.6 V | 2.4-3.6 V | 2.7-6.5 V |
| Dimensions | 4 mm x 4 mm | 4 mm x 5 mm | 2.16 cm x 2.03 cm |
| Package | QFN | LGA | SIP |

Table 3.2: Properties Gyroscopes


(a) MPU-6050 (b) LSM330DLC (c) 27911

Figure 3.2: Photos Gyroscopes

At this point a multi-criteria analysis would be applicable. However for the construction and testing of the prototype it is considered an advantage if the sensor can be soldered on a perfboard. This way it can be easily connected and tested and it creates space for unforeseen changes. Therefore the packages of socket of the sensors needs to fit on a perfboard. Only the 27911 complies with this request, hence two 27911 gyroscopes are chosen as sensors for the stabilised platform.

### 3.2.2. ACTUATORS

In section 3.1 it is decided via a multi-criteria analysis that the system will use three linear actuators for compensating the pitch and roll motion. These actuators will be controlled with a microcontroller, which process the input data from the two gyroscopes. In this subsection, a linear actuator is selected for this purpose.

The linear actuator must comply with the requirements for the prototype as described in chapter 2. The most important requirements for the actuator are: 2.1.4, 2.1.8, 2.2.2, 2.2.3, 2.2.5 and 2.2.7. In short this means that the actuators must fit into a virtual cylinder of 10 cm with a height of 30 cm. Additionally the actuators must be within budget, have a speed of 30 mm/s, have an minimal accuracy of 1 mm. The actuators must be able to tilt the platform to an angle of 37 °, with respect to the vertical. Given that the platform has a radius of 112 mm, the minimal length of the actuators can be calculated. This is 86 mm. Furthermore, each of the actuators must be able to support scaled weight of the ZephIR300 LiDaR. Given is that the scaled weight of the ZepIR300 LiDaR is 0.44 kg [$m$]. The maximum load per actuator can be calculated using Newton's second law of motion assuming that the accelerations arising out of platform tilting are small compared to gravity. See equation 3.1.

$$MaxLoad_{scaled} = m \times g = 4.32N \tag{3.1}$$

In other words the actuators need to comply with $Load_{perActuator} \geq 4.32$ N. From the selected microcontroller and PC power supply it can be deduced that the input voltage and power supply must be 3,3/5/12 V. Out of these requirements, the requirement about the budget in combination with the speed is the most challenging. For the available budget an actuator with limited speed can be purchased, although there are faster electric actuators on the market. The most suitable actuators found came from the same supplier: Firgelli. The budget has a higher priority than the speed so the chosen actuators remain within budget, but do not fit the speed requirement. The three actuators that are chosen are the L16-100-P [28], the L12-100-P [29] and the L12-100-S [29]. The properties of the most suited actuators are shown in table 3.3. An example of these actuators is shown in figure 3.3.

| Actuator | L16-100-P Firgelli | L12-100-P Firgelli | L12-100-S Firgelli |
|---|---|---|---|
| Price | €115.10 | €102.31 | €120.31 |
| Max Speed | 20 mm/s | 5 mm/s | 5 mm/s |
| Stroke | 98 mm | 100 mm | 100 mm |
| Max load | 75 N | 45 N | 45 N |
| Accuracy | 0.4 mm | 0.3 mm | 0.3 mm |
| Voltage | 12 V | 12 V | 12 V |
| Current | 650 mA | 200 mA | 200 mA |
| Position feedback | Yes | Yes | No |

Table 3.3: Properties Actuators

Figure 3.3: Photo Miniature Linear Motion Series L16

Given the requirements and properties as stated above, the selection of a suitable actuator is very complex. Hence, a multi-criteria analysis is chosen for the decision making. In this analysis price has the highest weight, because the budget is very tight and linear actuators are generally expensive when it comes to high speeds. Hence, speed is next in the list of priorities. After that, position feedback is considered valuable, because this can make the control more precise. Lower down on the list are accuracy and load. These are less of an issue, because the stabilisation may have a deviation of 5°, see requirement 2.1.2. The primary objective of the prototype is to give proof of principle. In the full-scale buoy, the selection of the actuator will be redone, based on the data received from the testing stage of the prototype. Besides the named properties there are no more relevant properties of the actuators. From this follows the multi-criteria analysis given in table 3.4. The L16-100-P actuator has the highest benefit, hence this actuator is chosen.

| Objective | Weight | L16-100-P | L12-100P | L12-100S |
|---|---|---|---|---|
| Price | x5 | 1 | 2 | 2 |
| Speed | x4 | 4 | -1 | -1 |
| Load | x1 | 2 | 1 | 1 |
| Accuracy | x2 | 1 | 2 | 2 |
| Position feedback | x3 | 1 | 1 | -1 |
| Total benefit | | 28 | 11 | 8 |

Table 3.4: Multi-Criteria Analysis for the Actuators

The L16-100-P is designed to push or pull a load along its full stroke length. The speed of travel is determined by the load applied. When in open circuit, the actuator will hold its position unless the applied load exceeds the restraining force. When voltage is applied to the motor the actuator extends. Reverse the polarity and the actuator retracts. This can be done using an H-bridge circuit.

An H-bridge needs to be selected to control the polarity of the voltage applied to the actuator. The H-bridge needs to supply 12 V, via the PC power supply, to the actuators. This H-bridge needs to be controlled with the microcontroller, which has output values of 3.3 V. The H-bridge needs a power supply of 5 V. Lastly, the H-bridge needs to be within budget. Based on this criteria demands the L298n H-bridge [30] is selected. This H-bridge meets all the demands and can support up to two actuators per chip. Therefore two H-bridges are needed.

The actuator has a limit switch that will turn off power to the motor when the actuator reaches within 1 mm of the end of the stroke. This scenario is however not sought after because, in time, it might cause damage to the actuators. To avoid this risk, the position feedback can be used to stop the actuator at the start and the end of the stroke length. The position feedback consists of an analog signal from each actuator.

Because the microcontroller does not have three analog input channels for the actuator position feedback these inputs will need to be processed in a separate circuit. This circuit is not part of the scope as it related to the microcontroller. The circuit is constructed using LM339N comparators which compare the position feedback signal to the limit values of the start and end position of the stroke length. The microcontroller gets a signal when the actuator is in either of those positions so it can stop the extending or retracting of the actuator.

### 3.2.3. LINKAGES

In section 3.1 it is explained that linkages need to be selected and that a choice needs to be made according to the amount of linkages that are used. First the choice of the actual linkages will be discussed after which the choice for the amount of linkages is made.

(a) Ball Joint

(b) Universal Linkage

Figure 3.4: Photo Linkages

There are two types of linkages that can be used as hinge for the platform, see figure 3.4. The two types are universal linkages and ball joints. The choice between the two linkages depends on two factors: the size of the linkage and the maximum rotation it can undergo.

The size of the linkage must be in proportion to the actuators to ensure that the connections run smoothly. It is thereby set as a specification. The maximum size of the linkages are set at roughly 25% of the maximum length of the actuator. The maximum size is therefore 5 cm.

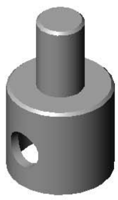
With this maximum size determined two linkages are selected and the remaining factor is examined. The maximum angle the linkages can rotate can be found in table 3.5.

| Linkage | Maximum Angle |
|---|---|
| Huco Universal Joint 103.06.1414 | 45° |
| Steel ball & socket joint, M6x1mm | 20° |

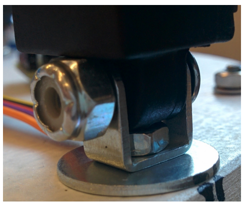
Table 3.5: Maximum Angle Linkages

Because of requirement 2.2.3, the angle that the linkages must be able to rotate is 37°. Because of that requirement the choice for the linkage is the Huco Universal Joint.

To attach the linkages to the actuators some kind of connecting component needs to be fashioned since no regular part exists. This part will need to fit onto the actuators and connect to the linkage. All this needs to be done without any play. The part that is designed can be found in figure 3.5a. More detailed specifications can be found in appendix C.



(a) The Connector Between the Actuator and the Upper Linkage



(b) Standard Equipment Linkage Below the Actuator

Figure 3.5: Photos Connector & Linkage

Lastly, the choice for the amount of linkages has to be made. This choice depends on the desired degrees of freedom, see figure 3.6, and the play at the joints. If joints are not exactly stable, unwanted degrees of freedom can occur. The linkages can be either placed above the actuators, below the actuators or both.

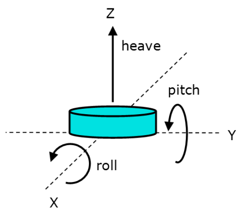



Figure 3.6: Degrees of Freedom Platform

First, formula 1.1 is used to calculate the degrees of freedom of the linkages. Assuming the platform has 3 DOF, partial heave compensation included, while the platform is active and 0 DOF while it is locked the needed DOF of the linkages can be calculated. The linkages on top of the actuators need to have 2 DOF and must be able to rotate 45°. The linkages selected previously can be used for that purpose. The linkages below the actuator need to have 2 DOF but don't have any requirements about the angle they need to be able to rotate. Therefore, these linkages can be the linkages that are standard equipment of the actuators, see figure 3.5b. These linkages have play in the perpendicular axis of the linkage and can thus handle in two DOF.

From formula 1.1 it can also be concluded that a fixed support is not needed to restrict the number of degrees of freedom. The platform is, in theory, stable by itself. It can however be useful when, during testing, the platform proves to be sensitive to translational movements. The option to implement a fixed support is thereby left open and the fixed support can be implemented after testing if necessary.

## 3.3. ASSEMBLY

The components discussed in section 3.2 need to be connected. This can be done by following the schematic in figure 3.8. Based on the selected components the topology as described in figure 3.1 is adjusted. Two H-bridges are added to drive the actuators and the fixed support is removed. The H-bridge can be found in figure 3.7.

The new topology of the platform can be found in figure 3.9. This also shows the exact placement of each component. After connecting the components the platform looks like figure 3.10.

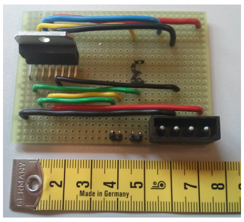


Figure 3.7: Photo H-bridge

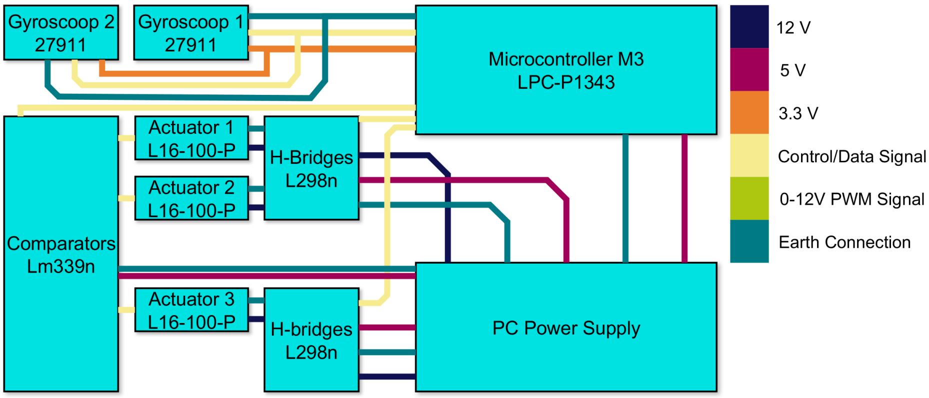



Figure 3.8: Schematic Outlay of the Electronics of the Platform

## 3.4. OPERATION OF THE PLATFORM

The platform will be used for compensating the pitch and roll movement of the buoy as a result of sea waves. This platform has a maximum compensating speed of 15 °\ s and can reach a theoretical maximum angle of 41.8 °. The platform can carry a load of 7.6 kg. The dimension of the platform (excl. power supply, microcontroller and H-bridges) is cylindrical with a radius of 112 mm and a maximum height of 365 mm.

The platform operates by measuring the angular velocity from both the sensors and integrating this into an angular displacement. By calibration and comparing the data of the gyroscopes the angle to be compensated can be calculated. This is done with a microcontroller which communicates with the gyroscopes via $I^2C$. The

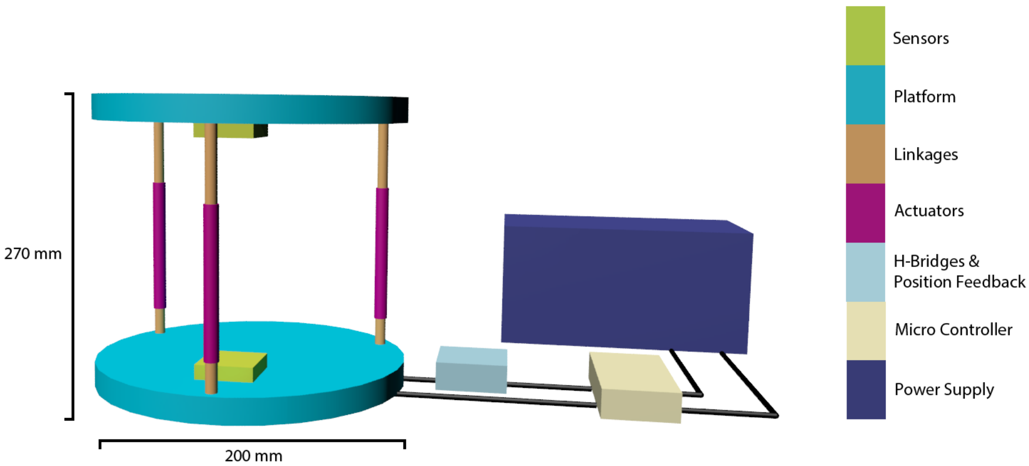



Figure 3.9: Adjusted Topology of the Actively Stabilised Platform

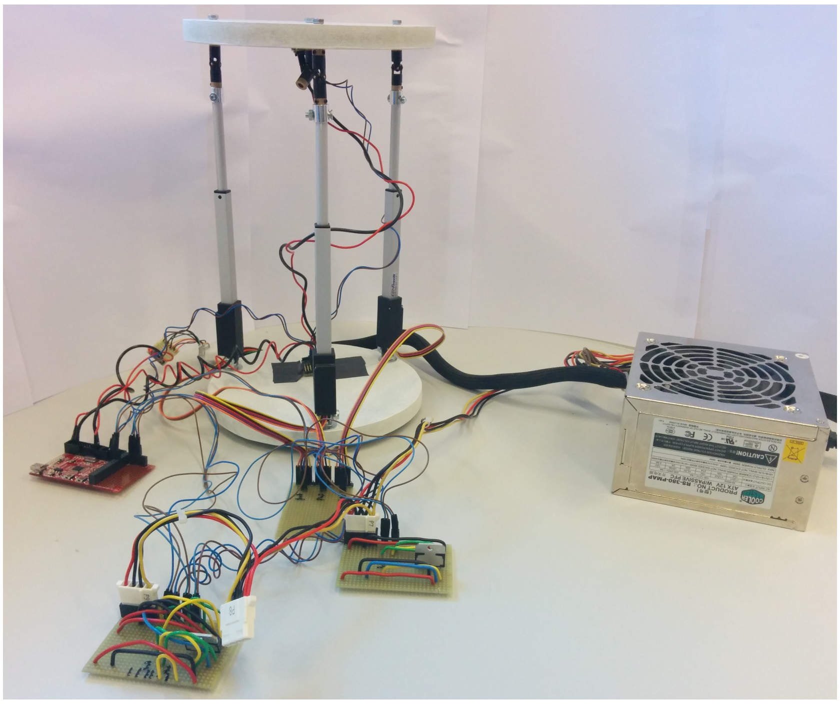


Figure 3.10: Photo of the Platform

microcontroller then calculates the output to control H-bridges which applies the required voltage with the correct polarity to the actuators.

## 3.5. TRANSFORMATION TO THE FULL SCALE BUOY

For the full scale buoy a few changes need to be applied. For instance, the sensors do not necessarily need to have packages or additional sockets which fit on a perfboard. They will be processed with the other electronics into a PCB. This PCB is thereby a second difference with respect to the prototype. Furthermore, the budget of the full-scale buoy will allow more costly actuators with higher speed. These actuators can be linear electric actuators but hydraulic and pneumatic actuators are viable alternatives. Additionally, the full scale buoy will have a battery pack instead of a PC power supply, which can cause a change in the requirements for the components. Also most of the components need to be rescaled to full size, for example the platform and the linkages.

Besides these changes, the design remains similar in essence, like the placement of the components and the number of actuators. This prototype will thereby give proof of principle, which can be used for the full scale buoy.

# 4

# Overall Design of the Buoy

In the following chapter the overall design of the buoy is discussed. The goal of this buoy is to stabilise wind measurement equipment, also known as the ZephIR300 LiDaR, to prevent errors. A second objective of the goal is to add autonomous position control. In order to do that an existing SEAWATCH Wind LiDaR buoy is modified. The modification require two major changes: adding an actively stabilised platform, that will stabilise the ZephIR300 LiDaR, and an autonomous position system which includes propulsion.

The topology of the buoy is discussed in section 4.1. The main parts will be discussed in section 4.2. After that there will be a short description about how the parts are linked together in section 4.3. The usage will be discussed in section 4.4. Lastly, the most important differences between the scaled prototype and the full scale buoy are discussed in section 4.5.

## 4.1. Topology Buoy

The prototype of the buoy needs to comply with the requirements set in chapter 2. For the overall buoy design the most important requirements are 2.2.10, 2.1.6 and 2.2.8. These requirements state that the prototype must be a close replica of the SEAWATCH Wind LiDaR buoy, must be scaled with 1:5 and all the components need to be waterproof or made waterproof.

In figure 4.1 a schematic of the buoy is shown. This is an exact replica of the SEAWATCH buoy with the actively stabilised platform and the autonomous position control pictured. This buoy consist of five parts.

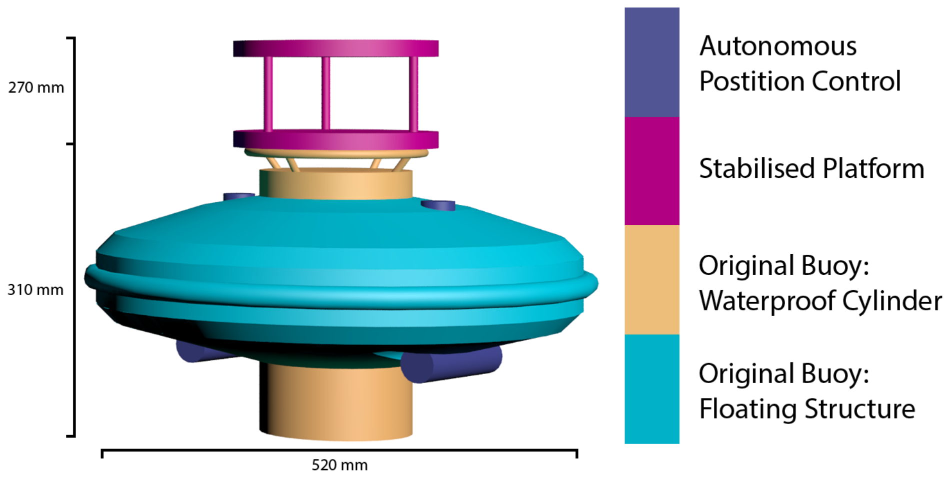



Figure 4.1: Schematic Overview of the Prototype Buoy

- First of all the ZephIR300 LiDaR: this is an existing piece of technology with the purpose to measure wind speed and direction, by shooting laser pulses into the air and analysing the back scatter. The pitch and roll of the sea waves can disturb the measurements of the ZephIR300 LiDaR, leading to errors. In this thesis the ZephIR300 LiDaR is considered out of the scope. Only the scaled dimensions need to be known, the weight and the angle at which the measurements are disturbed.
- The figure also shows the autonomous position control. This part is needed to sail to a given position and maintain this position. The placing of the different components is discussed further in subsection 4.2.1.
- Another part is the stabilising platform. This part is used to stabilise the ZephIR300 LiDaR and will be discussed in subsection 4.2.2.
- The two remaining parts, the waterproof cylinder and the floating structure, are considered the hull of the buoy and will be discussed in subsection 4.2.3. These parts match the dimensions of the SEAWATCH Wind LiDaR Buoy, but are still discussed because they are vital to establish proof of principle for the buoy.

## 4.2. MAIN PARTS

In this section the main parts of the buoy will be discussed. The autonomous position control in subsection 4.2.1, the stabilised platform in subsection 4.2.2 and the hull of the buoy in subsection 4.2.3. The hull is hereby considered as both the waterproof cylinder and the floating structure.

### 4.2.1. AUTONOMOUS POSITION CONTROL

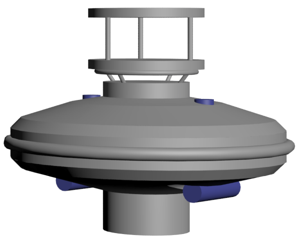


Figure 4.2: Schematic Overview Autonomous Position Control

This subsection the position of the autonomous position control within the design of the overall buoy is discussed, see figure 4.2. The design of the autonomous position control is discussed in a separate thesis [11]. The purpose is to autonomously control its position on sea. The position on the buoy must comply with the requirements from chapter 2. The most important requirements considering the autonomous position control are requirements 2.1.5, 2.2.11 and 2.2.12. In short this means that a place must be reserved for the propulsion equipment which allows the buoy to be able to sail and steer.

The design of the autonomous position control consists of a microcontroller, the LPC-P1343, a GPS module, the NL-552ETTL, two motors with propellers, the COMO drills 919D2.51, the electronics which drive the motor and two H-bridges to control the drive. The system is powered with a PC power supply.

The microcontroller is chosen in such a way that it can also control the platform and thus will be shared between the two parts. This component is not waterproof and will be located in the waterproof cylinder as will be discussed in subsection 4.2.3. The same applies for the electronics with an exception for the GPS module. The GPS module will be fitted on the outside of the buoy above sea-level. This is done to allow the GPS module to receive and send data. It will be connected with the electronics in the waterproof cylinder through a hole at the top of the waterproof cylinder, which is glued to waterproof it.

The DC-motors must be fitted on the same axis on both sides of the cylinder, see figure 4.3. The motors are already modified to be waterproof. The connection to the electronics inside the waterproof cylinder also needs to be waterproof. The wiring will be connected to the waterproof cylinder via a hole on top of the cylinder. The connection is waterproofed by gluing it. As a safety measure a 5 Ampere fuse is fitted between the DC-motors and the electronics.

The power supply will be placed onshore and outside the buoy, hence there has to be a long power connection from the shore to the buoy and inside the waterproof cylinder. This is done through the same connection as the autonomous position control and GPS module.

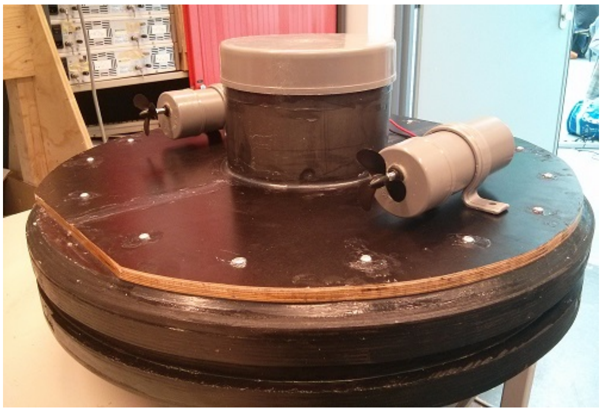


Figure 4.3: Photo Placement of the DC-motors (Buoy is Upside Down)

### 4.2.2. ACTIVELY STABILISED PLATFORM

In this subsection the position of the actively stabilised platform within the overall design of the buoy is discussed, see figure 4.4. The design of the platform is discussed in chapter 3. The purpose of the platform is to stabilise the wind measurement equipment, also known as the ZephIR300 LiDaR. The position of the platform must comply with the requirements set in chapter 2.

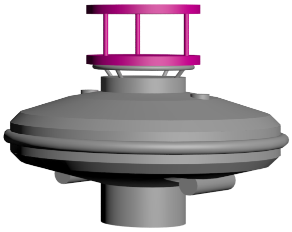


Figure 4.4: Schematic Overview Actively Stabilised Platform

The platform consists of the physical platform, which is formed from three actuators, two gyroscopes, two circular plates and six linkages. The system is controlled via three H-bridges and a microcontroller. Everything is powered with a PC power supply. The physical platform is mounted on the hull as shown in figure 4.5.

The gyroscopes need to be made splash water proof with tape. The actuators have already been made splash waterproof. The microcontroller is shared with the autonomous positioning control and is, together with the H-bridges, inside the waterproof cylinder. The connection with the platform happens via a hole in the top of the cylinder which also connects the GPS module and the power supply. This hole is waterproofed by gluing it shut.

Figure 4.5: Photo Placement of the Platform

### 4.2.3. THE HULL OF THE BUOY

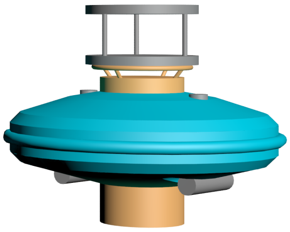


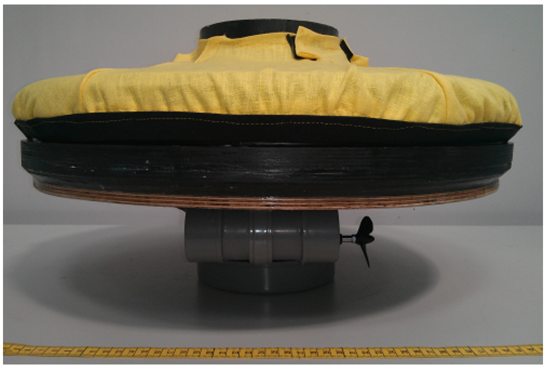
Figure 4.6: Schematic Overview of the Hull of the Buoy

In this subsection the hull of the buoy will be discussed, see figure 4.6. The hull consists of a waterproof cylinder and a floating structure. Both these parts are designed to the scaled dimension of the SEAWATCH Wind LiDaR Buoy. The purpose of these parts is to make a buoy on which the stabilised platform and autonomous position control can me mounted. This is done to make a complete prototype and to be able to test that prototype. The hull needs to comply with the requirements described in chapter 2. The most important requirements are requirements 2.1.6, 2.2.8 and 2.2.9. In short this states that the hull must be an exact 1:5 scaled replica of the buoy and be able to float.

The waterproof cylinder is made from a PVC drain pipe with two matching lids for each side. The bottom lid is glued with PVC-glue and on top of that glued shut with waterproof kit. The top side of the PVC drain pipe only needs to be splash waterproofed, hence this is just clamped on top. The upper lid also has a hole for wire connections in both directions. This is done in order to connect the electronics on the inside with the power supply, the GPS module and the stabilised platform.

The floating structure is made up from layers of water resistant multiplex cut into half circles and glued together. The bottom is shut with one piece of water resistant multiplex and the top is made splash water proof with a hood of canvas. The result can be found in figure 4.7. Due to the fact that the prototype is built as an exact replica of the buoy the structure will be expected to float.

(a) Auxiliary View Buoy



(b) Sideview Buoy

Figure 4.7: Photo of The Hull and Waterproof Cylinder of the Prototype

## 4.3. ASSEMBLY

The components discussed in section 4.2 need to be connected. This can be done following the schematic in figure 4.8. This overview only depicts the main parts. The exact components can be found in their corresponding subsections. The power supply is also not pictured in the overview.

After connecting all the components and mounting every part onto the prototype the prototype is finished. The prototype can be found in figure 4.9.

## 4.4. OPERATION OF THE BUOY

The full scale buoy will be used to perform wind measurements offshore. With this prototype the functions needed to operate offshore can be tested. The system includes wind measurement equipment in the form of the ZephIR300 LiDaR. This equipment is actively stabilised with an stabilising platform. Furthermore the buoy can control its own position via a GPS module. This enables users to control the position of the buoy. It also enables users to let the buoy navigate to any given position and retain its new position.

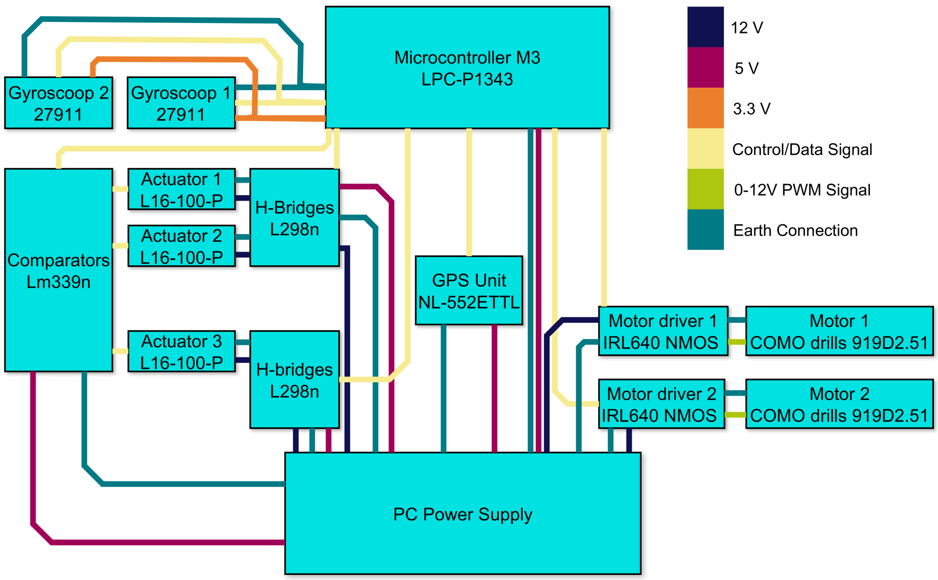
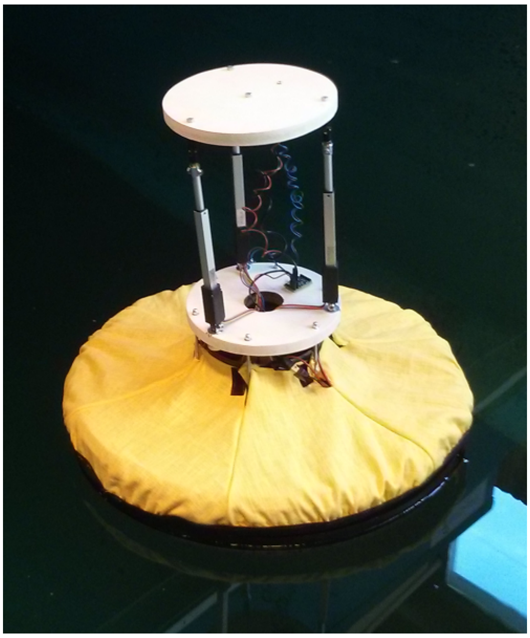



Figure 4.8: Schematic Outlay of the Electronics of the Finished Buoy

(a) Photo of the Finished Buoy



(b) Photo of the Finished Buoy in the Test Basin

Figure 4.9: Photos Finished Buoy

## 4.5. TRANSFORMATION TO THE FULL SCALE BUOY

The transformation of the overall design to the full scale buoy differs from the overall design of the prototype. For example the buoy itself will already exist, hence a scaled-up actively stabilised platform only needs to be mounted on top of the SEAWATCH Wind LiDaR buoy. Also the GPS module and the propulsion equipment need to be fitted on the full scale buoy. The fixtures will need to be waterproof as will the connections. The power supply for the prototype falls outside of the scope, but for the full scale buoy an on board solution needs to be found for power supply.

# 5
# Testing and Results

In the following chapter the testing of the prototype is discussed as well as the results of the testing. The testing is done at the basis of testing criteria which can be found in section 5.1. In section 5.2 the test setups of the prototype are discussed and in section 5.3 the results of the tests are presented. Lastly, the test results are discussed in section 5.4.

## 5.1. Testing Criteria

In the following section the testing criteria for the prototype will be discussed. This can be found in subsection 5.1.1. In subsection 5.1.2 the testing of the full scale buoy is discussed.

### 5.1.1. Testing of the Prototype

To be able to tell if the prototype works properly it will need to comply with the design objectives. Therefore it will need to comply with the design requirements drafted from the objectives. To show that the prototype complies with the requirements testing criteria are drafted.

**Geometry Test**

The layout and scale of the prototype need to be tested. The design of the prototype inherently takes into account some of the core requirements which are discussed in chapter 4. The prototype therefore already complies with requirements 2.1.4 and 2.1.5. Requirements 2.1.6 and 2.2.8 need to be tested to make sure the prototype is valid. This is done by comparing the SEAWATCH Wind LiDaR Buoy, the 3D model of the scaled SEAWATCH Wind LiDaR Buoy and the actual prototype. The requirements can be found in table 5.1.

| Requirement ID | Test Question | Test |
|---|---|---|
| Requirement 2.1.6 | Does the prototype closely resemble the SEAWATCH Wind LiDar Buoy? | Geometry Test |
| Requirement 2.2.8 | Is the prototype built to scale? | Geometry Test |

Table 5.1: Layout and Scale Requirements that need to be Tested

**Water Test**

The floatability, requirement 2.2.9, the waterproofing, requirement 2.2.10, and the sailing, requirements 2.2.11 and 2.2.12 of the prototype must be tested. The first two requirements are used in the design process but both need to be tested. The method of testing these requirements is obvious. The prototype will be launched into water and will then try to sail in a straight line. After that it will try to make a turn. This way all requirements are tested. If one of the requirements fails, an individual test may be performed. The requirements can be found in table 5.2.

| Requirement ID | Test Question | Test |
|---|---|---|
| Requirement 2.2.9 | Does the prototype float? | Water Test |
| Requirement 2.2.10 | Is everything on the prototype waterproof? | Water Test |
| Requirement 2.2.11 | Can the prototype sail? | Water Test |
| Requirement 2.2.12 | Can the prototype steer while sailing? | Water Test |

Table 5.2: Floatability, Waterproofing and Sailing Requirements that need to be Tested

**Platform Tests** The stabilisation platform must be tested. The design of the platform inherently takes into account some of the core requirements which are therefore discussed in chapter 3. The prototype therefore already complies with requirements 2.2.1, 2.2.4, 2.2.5, 2.2.6 and 2.2.7. The additional requirements that need to be tested are stated in table 5.3. To test the requirements a test setup is designed.

| Requirement ID | Test Question | Test |
|---|---|---|
| Requirement 2.1.1 | Can the platform control the pitch as well as the roll motion? | Platform Test 2 |
| Requirement 2.1.2 | Does the platform return to a stabilised state within 5°? | Platform Test 2 |
| Requirement 2.1.3 | Can the platform get to a stabilised state in under 1 second? | Platform Test 2 |
| Requirement 2.2.2 | Can the platform support 0.44 kg while doing the tests? | Platform Test 2 |
| Requirement 2.2.3 | Can the platform take on an angle of 37°? | Platform Test 1 |

Table 5.3: Platform Requirements that need to be Tested

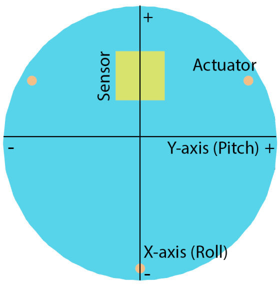



Figure 5.1: The Definition of Pitch and Roll with Respect to the Actuators

The working of the platform will be tested with two tests. The first test is used to test the maximal angle the platform can tolerate in the pitch as well as the roll motion, see figure 5.1. This test is conducted by manually setting the platform under its maximal degree of tilt and verifying the angle by hand. The second test will have a few more steps.

The second test will be used to determine if the platform is able to compensate the pitch and roll movement under 1 second while a mass of 0.44 kg is on top of the platform. The platform is compensated when it returns to the stable state within 5 ° with respect to gravity.

This test will be conducted in eight different test scenarios for as well the pitch and the roll. The platform will be placed under 10 °, 20 °, 30 ° or 40 ° with or without a mass of 0.44 kg placed on top of the platform. The platform is then tasked to stabilise itself. The numbered test scenarios can be found in table 5.4. With each test scenario the following characteristics will be measured:

- The time it takes the platform to stabilise within its margin of 5°.
- The angle of the platform after stabilisation with respect to gravity.

To ensure that the test results are not depended on a single measurement all the scenarios are tested four times. The final test result will be the mean value of the four results.

| | Pitch | | Roll | |
|---|---|---|---|---|
| Angle | 0 [kg] | 0.44 [kg] | 0 [kg] | 0.44 [kg] |
| 10 ° | 1 | 5 | 9 | 13 |
| 20 ° | 2 | 6 | 10 | 14 |
| 30 ° | 3 | 7 | 11 | 15 |
| 40 ° | 4 | 8 | 12 | 16 |

Table 5.4: Testing Scenario's for the Platform

**Miscellaneous Tests**

Some of the requirements are not addressed in the sub-subsections above. These requirements, 2.1.7 and 2.1.8, will be individually addressed in section 5.3. The requirements can be found in table 5.5.

| Requirement ID | Test Question | Test |
|---|---|---|
| Requirement 2.1.7 | Has the prototype been built within two months? | Miscellaneous Test 1 |
| Requirement 2.1.8 | Has the prototype been built within budget? | Miscellaneous Test 2 |

Table 5.5: Miscellaneous Requirements that need to be Tested

### 5.1.2. TESTING THE FULL SCALE BUOY

When looking at the full scale buoy instead of the prototype, multiple changes need to be made in the testing criteria. Since the full scale buoy will not be tested in this thesis this part is purely theoretical. The full scale buoy needs to be tested in a completely different manner than the prototype. Because of its size most of the tests for the prototype can't be applied and need to be scaled up. Next to that, the buoy has additional requirements concerning its construction and operations.

In table 5.6 the design requirements of the full scale buoy are stated. Each requirement is examined and for each requirement it is determined what should be tested. This is just an indication, the complete testing criteria will need to be determined when the full scale buoy is built.

| Requirement ID | Testing Question |
|---|---|
| Requirement 2.1.1 | Can the platform control the pitch as well as the roll motion? |
| Requirement 2.1.2 | Does the platform return to a stabilised state within 5°? |
| Requirement 2.1.3 | Can the platform get to a stabilised state in under 1 second? |
| Requirement 2.1.4 | Does every component fit in the virtual cylinder on top of the buoy? |
| Requirement 2.1.5 | Does the propulsion equipment fit under the full scale buoy? |
| Requirement 2.2.1 | Does the ZephIR300 LiDaR fit on the platform? |
| Requirement 2.2.2 | Can the platform support 55 kg while doing the tests? |
| Requirement 2.2.3 | Can the platform take on an angle of 37°? |
| Requirement 2.2.4 | Do the sensors have a scale of 90 °/s and a sensitivity of 0.5 °/s? |
| Requirement 2.2.5 | Do the actuators have an accuracy of 1 mm? |
| Requirement 2.2.6 | Do the sensors have a process time of 2 ms? |
| Requirement 2.2.7 | Do the actuators have a speed of 40 mm/s? |
| Requirement 2.2.9 | Does the full scale buoy float? |
| Requirement 2.2.10 | Is everything on the full scale buoy waterproof? |
| Requirement 2.2.11 | Can the full scale buoy sail? |
| Requirement 2.2.12 | Can the full scale buoy steer while sailing? |
| Requirement 2.3.1 | Can the buoy operate in the weather conditions of the North Sea for 1 month? |
| Requirement 2.3.2 | Is the buoy able to be self-sufficient in its energy consumption for 1 month? |
| Requirement 2.4.1 | Does the stabilised platform unit consume 75 W or less? |
| Requirement 2.4.2 | Does the autonomous position control unit consume 125 W or less? |
| Requirement 2.4.3 | Are the different parts of the design of the full scale buoy dependant on each other? |
| Requirement 2.4.4 | Can the design of the full scale buoy be easily expanded? |
| Requirement 2.4.5 | Does the buoy comply with the stated European regulations? |
| Requirement 2.4.6 | Are 70% of the components used recyclable? |
| Requirement 2.4.7 | Do the production costs of the full scale buoy exceed € 50.000,-? |

Table 5.6: Testing Criteria for the Full Scale Buoy

## 5.2. TEST APPROACH

The testing of the prototype will be done on the basis of the testing criteria determined in section 5.1. In subsection 5.2.3 the test setup of the platform will be discussed. In subsection 5.2.1 the test setup of the geometry test will be addressed and in subsection 5.2.2 the water test setup will be discussed.

### 5.2.1. THE GEOMETRY TEST

The SEAWATCH Wind LiDaR Buoy can be found in figure 5.2a. The 3D model that is compared to the prototype is made with the 3D program Autodesk 3DS Max and can be found in figure 5.2b. The comparison between the model and the actual prototype can be found in figure 5.2.

(a) SEAWATCH Wind LiDaR Buoy (b) The Modified 3D Model (c) Photo of The Prototype

Figure 5.2: The Comparison of the SEAWATCH Wind LiDaR Buoy, the 3D Model and the Prototype

### 5.2.2. THE WATER TEST

The test setup for the water test can be found in figure 5.3. First the prototype is launched in the water and checked for leaks. After that, the engines are driven and the prototype tries to sail in a straight line. Then, the prototype tries to make a turn.

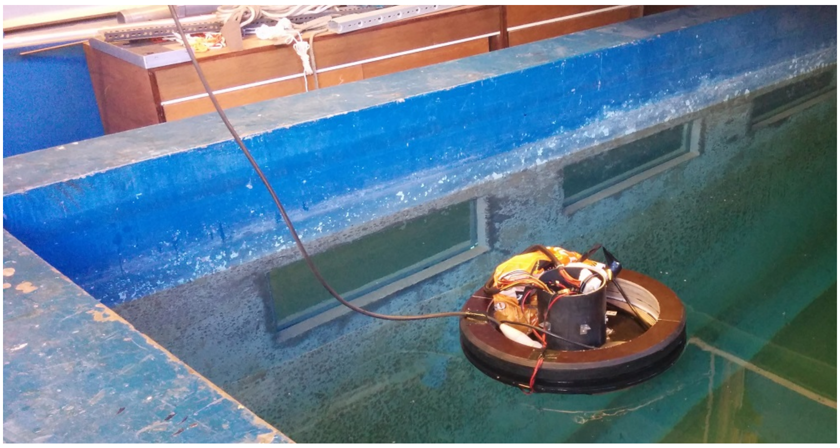


Figure 5.3: Photo of The Test Setup for the Water test

### 5.2.3. THE PLATFORM TESTS

The test setup for testing the platform can be found in figure 5.4. First the maximal angle of the platform is determined by manually setting the platform in that position with a spirit level and a protractor. After that the test scenario's described in subsection 5.1.1 are executed at the basis of a stopwatch and the same spirit level and protractor.

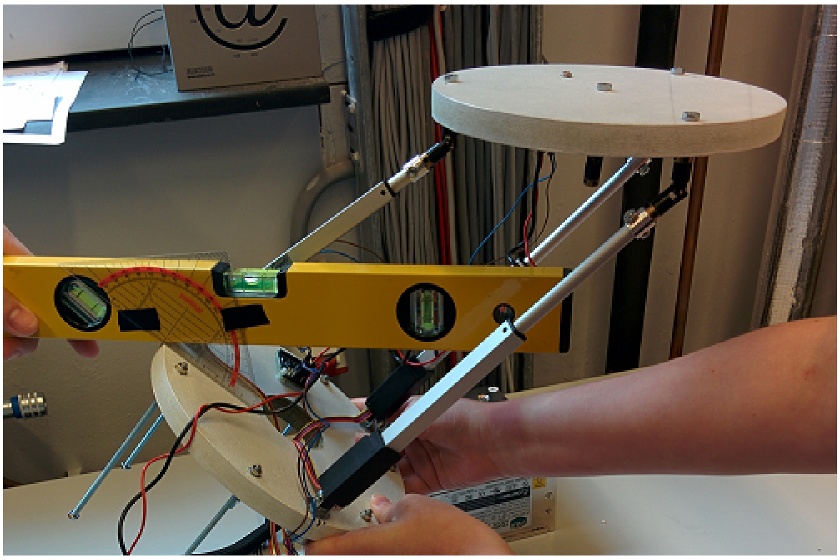


Figure 5.4: Photo of The Test Setup for the Platform Test

### 5.2.4. THE MISCELLANEOUS TESTS

The test setup for the miscellaneous tests consist of two parts. The first part looks at the time limit and the time it actually took to build the prototype and compares them. The second part looks at the budget, results and balance which can be found in appendix A and compares them.

## 5.3. RESULTS

In the following section the results of the testing of the prototype are discussed. In the subsection 5.3.3 the results of the platform test are presented. In subsection 5.3.1 the results of the geometry test are presented. The results of the water tests are presented in subsection 5.3.2. Last, the results of the miscellaneous tests are presented in subsection 5.3.4.

### 5.3.1. RESULTS OF THE GEOMETRY TEST

The testing of the geometry consists of comparing the virtual model of the SEAWATCH Wind LiDaR Buoy to the actual prototype. The measurements of the prototype are compared with the measurements of the 3D model of the buoy and the results can be found in table 5.7.

| Part | Measurements 3D model | Measurements Prototype |
|---|---|---|
| Platform Height | 206 [mm] | 206 [mm] |
| Platform Width | 224 [mm] | 200 [mm] |
| Buoy Structure Height | 289 [mm] | 279 [mm] |
| Buoy Structure Width | 526 [mm] | 526 [mm] |

Table 5.7: Comparison of Measurements of the 3D Model and the Prototype

To compare the looks of the prototype and the SEAWATCH Wind LiDaR Buoy the figures from subsection 5.2.1 were compared.

### 5.3.2. RESULTS OF THE WATER TEST

The testing of the water requirements consist of launching the prototype into water and then try to let the prototype sail in a straight line and let it perform a turn.

The prototype is able to float. Furthermore, everything underwater is waterproof and everything outside of the waterproof cylinder is splash waterproof.

The prototype is also able to sail at different speeds. Sailing in a straight line is somewhat difficult because the two propellers do not have identical power characteristics. This causes the buoy to lean to one side. It is able to steer, by only using one propeller at the time. The turn to the right takes a bit longer than the turn to the left because the right propeller has more power than the left propeller.

### 5.3.3. RESULTS OF THE PLATFORM TESTS

The testing of the platform consists of two tests. The first test determines the maximal angle of the platform and the second test determines if the platform is able to compensate the pitch and roll movement under 1 second while a mass of 0.44 kg is on top of the platform. The platform is considered compensated when it returns to the stable state within 5° with respect to gravity.

Results of the first test can be found in table 5.8. The maximal angle of the platform is measured in the pitch as well as the roll direction.

| Angle | Pitch | Roll |
|---|---|---|
| Maximal angle of the platform | 41 [°] | 38 [°] |

Table 5.8: Testing Results of the Maximal Angle of the Platform

The results of the second test are presented in two tables. The results of the time it takes the platform to stabilise can be found in table 5.9. The results of the angle of the platform after stabilisation can be found in table 5.10.

| | Pitch | | Roll | |
|---|---|---|---|---|
| Angle | 0 [kg] | 0.44 [kg] | 0 [kg] | 0.44 [kg] |
| 10 ° | 1,05 [s] | 1,24 [s] | 1,24 [s] | 1,20 [s] |
| 20 ° | 1,81 [s] | 2,06 [s] | 1,76 [s] | 1,96 [s] |
| 30 ° | 2,37 [s] | 2,55 [s] | 2,76 [s] | 2,60 [s] |
| 40 ° | 2,97 [s] | 3,15 [s] | 2,87 [s] | 3,20 [s] |

Table 5.9: Testing Results of the Time to Stabilise the Platform

| | Pitch | | Roll | |
|---|---|---|---|---|
| Angle | 0 [kg] | 0.44 [kg] | 0 [kg] | 0.44 [kg] |
| 10 ° | 0,5 [°] | -1,5 [°] | -3,3 [°] | 1,3 [°] |
| 20 ° | 1,3 [°] | -1,0 [°] | -2,5 [°] | 0,0 [°] |
| 30 ° | 0,3 [°] | -1,0 [°] | 0,8 [°] | -1,3 [°] |
| 40 ° | -1,3 [°] | -1,3 [°] | -3,3 [°] | 0,5 [°] |

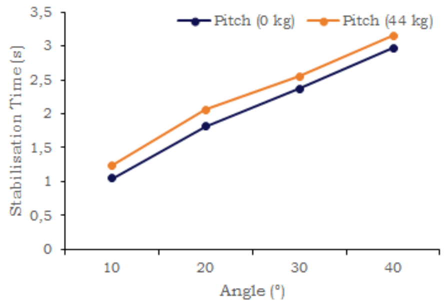
Table 5.10: Testing Results of the Angle after Stabilisation of the Platform

The results presented in tables 5.9 and 5.10 are plotted in figure 5.5. In subfigures 5.5a and 5.5c the time it takes the platform to stabilise can be found. In subfigures 5.5b and 5.5d the final angle of the platform after stabilisation can be found.

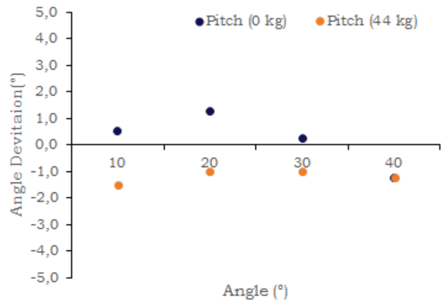
### 5.3.4. RESULTS OF THE MISCELLANEOUS TESTS

The testing of the miscellaneous consists of answering the two questions presented in section 5.1.1: "Has the prototype been built within two months?" and "Has the prototype been built within budget?".

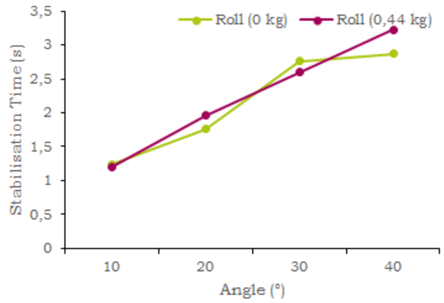
The design and building phase of the prototype took eight weeks. Besides that the total spending of the budget to build the prototype was € 794,93. More information about the budget can be found in appendix A.



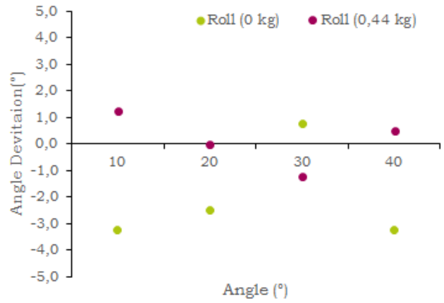

(a) Time to stabilise platform from pitch




(b) Angle after stabilisation from pitch




(c) Time to stabilise platform from roll




(d) Angle after stabilisation from roll

Figure 5.5: Result Graphs of the Platform Test

## 5.4. DISCUSSION OF TESTING RESULTS

In the following section a critical review of the test results from section 5.3 is done. If requirements are not met, the results are put in the proper perspective and an explanation is given. The review of the results of the platform test can be found in subsection 5.4.3. The review of the geometry t can be found in subsection 5.4.1. The review of the results of the water test is given in subsection 5.4.2 and the review of the miscellaneous test in subsection 5.4.4. Lastly, a summary of the results is given in subsection 5.4.5.

### 5.4.1. DISCUSSION OF THE GEOMETRY TEST RESULTS

The results of the test can be found in subsection 5.3.1. First the results presented in table 5.7 are discussed. It can be seen that a couple of measurements of the prototype do not correspond with the 3D model. These differences occurred during the assembly stage from measurement mistakes. They are relatively small and can thereby be neglected when looking at the operations of the prototype. The prototype is therefore determined to be built to the scale 1:5.

From the comparison it is determined that the prototype closely resembles the SEAWATCH Wind LiDaR Buoy but still misses some features. Features that are still not present on the prototype are an antenna and the solar cells. These features are not essential for the operations of the prototype and are therefore not included.

### 5.4.2. DISCUSSION OF THE WATER TEST RESULTS

The results of the test can be found in subsection 5.3.2. The prototype is able to float and everything on the buoy is waterproof or splash waterproof. The prototype is therefore determined to comply with the set requirements.

The prototype is also able to sail although not in a straight line. For this requirement it was not required to sail in a straight line so the prototype complies with this requirement. It is however, advisable to modify the propellers to have identical power characteristics.

The prototype can steer as well because the propellers can be controlled separately. This determines that the prototype complies with the set requirement.

### 5.4.3. DISCUSSION OF THE PLATFORM TEST RESULTS

The results of the platform test can be found in subsection 5.3.3. First, the results of the first test will be discussed. The maximal angle that the platform can compensate differs between the pitch and the roll motion. This is explained by the placement of the actuators, see figure 5.1. The distance between the pivots differs between the pitch and roll motion and thus influences the maximal angle. Both angles fall within the set requirement.

From subfigures 5.5a and 5.5c it can be concluded that the platform will be able to stabilise from any degree of tilt within 3.2 s. If the platform only has a deviation of 10° it will be able to stabilise within 1.25 s. The time to stabilise, from any degree of tilt that lies between the two extremes, is approximately linearly dependant on the degree of tilt. Because the required stabilise time is 1 s, the prototype does not meet the set requirement. This can be explained by the lack of speed of the actuators which was a conscious design decision. It can also be concluded that the actuators are influenced by the added load. For pitch compensation a clear difference is noticeable but for roll compensation it is less clear. This might be an indication to verify the acquired test results as similar results for the pitch and roll compensation are expected. The test results might also be influenced by the test setup, for instance by mental chronometry or measuring via a protractor.

From subfigures 5.5b and 5.5d it can be concluded that the platform will always stabilise within the 5° deviation set by the requirements. The maximum deviation found was equal to 3.5°. It is also clear that the final degree of deviation does not depend on the original degree of tilt the platform needed to compensate.

From the entire figure 5.5 it can be concluded that the platform is able to compensate the pitch motion as well as the roll motion. It also can be concluded that the platform can stabilise while the scaled load of the ZephIR300 LiDaR is applied.

Another problem that was encountered was a complication with the actuators. The actuators are designed to create linear motion, but the movement of the platform creates a circular motion. This movement is absorbed by the linkages but because the linkages below the actuators were tightened to make sure no unwanted DOF occured, stress was created in the actuator. Since the actuators are not designed to withstand this stress this created some problems. The problem was solved by loosening the linkages.

### 5.4.4. DISCUSSION OF THE MISCELLANEOUS TEST RESULTS

The results of test can be found in subsection 5.3.4. The time the design and building of the prototype took was the stated time. There was no deviation from this requirement.

The costs of the prototype stayed within budget. The budget was spent in a different way than initially intended but caused no problems.

### 5.4.5. SUMMARY OF THE TEST RESULTS

The final results of the testing can be found in table 5.11. For each requirement the type of testing, the test that is used and the result of the test are noted.

| Requirement | Subject | Test used | Meets requirement? |
|---|---|---|---|
| Requirement 2.1.1 | Pitch and Roll compensation | Platform Test 2 | Yes |
| Requirement 2.1.2 | Max. allowed degree of tilt | Platform Test 2 | Yes |
| Requirement 2.1.3 | Max. compensation time | Platform Test 2 | No |
| Requirement 2.1.4 | Virtual cylinder | Chapter 4 | Yes |
| Requirement 2.1.5 | Layout of the propulsion | Chapter 4 | Yes |
| Requirement 2.1.6 | Scale | Geometry Test | Yes |
| Requirement 2.1.7 | Development time | Miscellaneous Test 1 | Yes |
| Requirement 2.1.8 | Budget of the project | Miscellaneous Test 2 | Yes |
| Requirement 2.2.1 | Measurements ZephIR300 | Chapter 3 | Yes |
| Requirement 2.2.2 | Weight ZephIR300 | Platform Test 2 | Yes |
| Requirement 2.2.3 | Max. angle to compensate | Platform Test 1 | Yes |
| Requirement 2.2.4 | Sensor accuracy | Chapter 3 | Yes |
| Requirement 2.2.5 | Actuator accuracy | Chapter 3 | Yes |
| Requirement 2.2.6 | Process time sensor | Chapter 3 | Yes |
| Requirement 2.2.7 | Actuator speed | Platform Test 2 | No |
| Requirement 2.2.8 | Replica SEAWATCH | Geometry Test | Yes |
| Requirement 2.2.9 | Floating prototype | Water Test | Yes |
| Requirement 2.2.10 | Waterproof | Water Test | Yes |
| Requirement 2.2.11 | Sailing | Water Test | Yes |
| Requirement 2.2.12 | Steering | Water Test | Yes |

Table 5.11: Testing Results of the Requirements of the Prototype

# 6

# Conclusions and Recommendations

In this chapter the conclusions of this design thesis are presented. Here the results obtained in chapter 5 will be compared with the earlier stated goals and objectives. This chapter is concluded with a series of recommendations for further development.

## 6.1. Conclusions

The goal of this project is described in chapter 1, section 1.4. The goal of the project is to:

*Design a scaled prototype of the SEAWATCH Wind LiDaR buoy equipped with: an actively stabilised platform, to account for pitch and roll measurement errors of the ZephIR300 LiDaR, and autonomous position control, to relocate and account for position drift.*

This thesis focuses on the design of the actively stabilised platform and the overall design of the prototype. The objectives of this thesis are like the goal stated in chapter 1. The objectives are:

1. Design of the actively stabilised platform.
2. Select best suited sensors for delivering input data for the platform controller.
3. Select best suited actuators for transforming output data to the motion of the platform.
4. Design a compact overall lay-out of the working prototype.
5. Build a prototype of the buoy.
6. Acquire test results for proof of principle.

Based on these objectives, requirements for the prototype are set in chapter 2, these are translated into the design in chapter 3 and 4 and tested in chapter 5.

From the results of the testing stage can be concluded that the built platform can maximally stabilise a angle of 38° within 3,2 s, when the scaled load of the ZephIR300 LiDaR is applied. When stabilised, the maximum deviation angle is 3,3°. The overall design of the buoy closely matched the scaled 1:5 dimensions of the SEAWATCH Wind LiDaR buoy, barring that two extra parts are added. The design is waterproof, floats and is able to sail in desired directions. The total project had a total duration of two months and stayed within budget.

From this we can draw the conclusion that all the requirements set in chapter 2, except for the maximum stabilisation time and the actuator speed, are met. This originates from the fact a trade-off needed to be made concerning the actuators.

It can therefore be stated that active stabilisation of LiDaR based technology and autonomous position control offshore is possible and effective. Given that enough budget is available to purchase suitable actuators.

## 6.2. RECOMMENDATIONS

Based on the results obtained in this project, the following recommendations for further development are given:

- For this project, budget was made available by Delft University of Technology. Although it was an extensive amount for a bachelor thesis, it was not sufficient for actuators that would comply with the requirements. The speed of the actuators is considered the bottleneck in the total stabilisation time of the platform, because this component is significantly slower than the other components used. For further development it is recommended to enlarge the budget in order to purchase faster actuators. In the selection of actuators, care needs to be taken by selecting actuators that are fast even when there is a large load applied.
- In testing the design a complication arose with the actuators. To make sure no unwanted rotations occured, the linkages below the actuators were tightened. This introduced a large amount of side load stress on the actuators since the platform describes a circular motion. In further development it is recommended to select actuators which have a case that is able to resist side load stress. Another solution is linkages at the bottom that have two controllable degrees of motion in order to avoid uncontrolled rotations.
- For the measurement of the pitch and roll movement to be compensated gyroscopes are used. However this system proves to be influenced to a large extent by noise. This comes from the fact that gyroscopes measure the angular velocity which has to be integrated in order to get the angular displacement, hence the noise will be integrated too. For this a combination between gyroscopes and accelerometers or inclinometers are recommended. This would make the measurement system more reliable.
- When testing the stabilisation time and the deviation angle of the platform, the test setup proved to be less reliable than desired. Mental chronometry and small deviations in the start angle had their effect on the amount of significant numbers in the test results. As a result the little overshoot of the platform could not be measured. Although insurmountable for this project, it is recommended to develop a more accurate test setup for future testing. This test setup should be completely computerised. For example a setup that uses gyroscopes to determine the deviation angle and time for start to stabilisation.
- The power supply falls outside the scope of this thesis. For powering a PC power supply is used. For further development the design of the power supply needs to be addressed. It is recommended to research and design a power supply that can manage the power consumption of the buoy for multiple days. The use of solar or wind energy is recommended.
- This thesis focuses on the compensation of two degrees of motion, the rotation around the x-axis an y-axis, also known as the pitch and roll. By doing this the measurements of the ZephIR300 LiDaR become more reliable because there is no need for post processing. For truly optimised measurements the translation in the z-axis, also known as the heave, should also be compensated. The platform is designed in such a way that partial heave compensation can be implemented, by altering the control code.

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# A

# BUDGET

**Budget**

| Product | Number | Price per unit | Price one-off | Final Price |
|---|---|---|---|---|
| Microcontroller | 2 | € 20.00 | | € 40.00 |
| AD/DA Transformer | 4 | € 10.00 | | € 40.00 |
| Actuators | 4 | € 30.00 | € 80.00 | € 200.00 |
| Compressors | 4 | € 30.00 | | € 120.00 |
| Sensors | 3 | € 50.00 | | € 150.00 |
| PCB | 2 | € 20.00 | | € 40.00 |
| Miscellaneous (Raw materials) | 1 | € 100.00 | | € 100.00 |
| Motors | 2 | € 15.00 | | € 30.00 |
| Unforseen | 1 | € 100.00 | | € 100.00 |
| Total | | | | € 820.00 |

**Results**

| Product | Number | Price per unit | Price one-off | Final Price |
|---|---|---|---|---|
| Actuators | 3 | € 115.00 | € 39.00 | € 384.00 |
| Sensors | 2 | € 26.29 | | € 52.58 |
| | | | | |
| **Miscellaneous (Raw materials)** | **0** | **€ 100.00** | | **€ 0.00** |
| ***Electronics*** | | | | |
| *H-Bridges* | *4* | *€ 6.09* | | *€ 24.36* |
| *Linkages platform* | *4* | *€ 4.24* | | *€ 16.94* |
| *Molex* | *4* | *€ 3.17* | | *€ 12.66* |
| *GPS Module* | *1* | *€ 49.98* | | *€ 49.98* |
| *Materials to connect DC Motors* | *1* | *€ 10.40* | | *€ 10.40* |
| ***Other Materials*** | | | | |
| *Propellors* | *2* | *€ 3.89* | | *€ 7.78* |
| *PVC drain pipe* | *1* | *€ 22.50* | | *€ 22.50* |
| *Small Materials for Assembly* | *1* | *€ 9.35* | | *€ 9.35* |
| *Material to waterproof Motors* | *1* | *€ 12.95* | | *€ 12.95* |
| *Fabric* | *1* | *€ 14.12* | | *€ 14.12* |
| *PVC drain pipe lids* | *2* | *€ 5.98* | | *€ 11.95* |
| | | | | |
| DC Motors | 2 | € 15.00 | | € 30.00 |
| **Unforseen** | **0** | **€ 100.00** | | **€ 0.00** |
| Extra Actuator | 1 | € 115.00 | € 20.36 | € 135.36 |
| | | | | |
| Total | | | | € 794.93 |

**Balance**

| | In | Out |
|---|---|---|
| Budget | € 820.00 | |
| Results | | € 794.93 |
| Total | € 25.07 | |

# B

# WAVE ANGLE CALCULATIONS FOR A NORTH SEA WIND FARM

The following calculations are made with information acquired through contacts within Ampelmann Operations BV. The source can therefore be traced through [31].

From all the data that is provided the data from wind farm Horns Rev 1 provides the most average samples of the "Wave Height versus Wind Speed" and "Wave Height versus Wave Period" data. With the data of this wind park the maximal angle of the wave and the maximal change of angle of the wave are calculated.

From the data in figure B.2a it can be concluded that all the data is relevant because wind farms still operate during the maximum wind speeds measured.

From the Wave Height versus Wave Period data in figure B.2b the maximal angle can be calculated. To simplify the calculation the wave is estimated to behave like a sinus function. To calculate the angle of the sinus with the x-axis the sinus function is linearised between $3\pi/4$ and $5\pi/4$, see figure B.1. The calculation can be found in equation B.1.

$$Angle = \arctan \frac{\frac{1}{2}\sqrt{2} \times H}{\frac{1}{4} \times P} \tag{B.1}$$

- $Angle$ = Maximal angle of the wave
- $H$ = Height of the wave
- $P$ = Period of the wave

In figure B.3a the maximal angle for every combination of wave height and wave period can be found. Some angles are high, around 60°, but rarely occur. In order to account for the frequency of which the angles concur it is decided to analyse the lowest 80% and determine the maximal angle of that data. The maximal angle of the waves is therefore determined to be 37°.

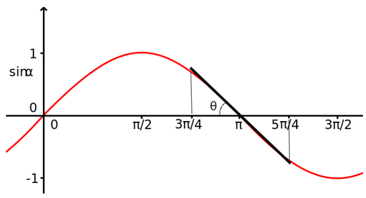



Figure B.1: Linearisation of the Sinus

The maximum angle of the wave is determined but the change of angle per second [°/$s$] still needs to be determined. From the data in figure B.2b the function of the sinus can be determined. When the derivative of the sinus is taken and set to zero the maximal angle per second can be determined like the maximal angle is determined too. The first part of the calculations can be found in equation B.2, the second part is the same as in equation B.1. The results of the calculations can be found in table B.3b. The maximum angle per second is determined to be 28.6 °/s.

$$\frac{\partial}{\partial t}\left(\frac{1}{2}H\sin(\frac{\pi}{\frac{1}{2}P}t)\right)=0 \tag{B.2}$$

- $t$ = Time
- $H$ = Height of the wave
- $P$ = Period of the wave

Wind Speed [m/s]

Wave Height [m]

| | lower | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | 28 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| lower | upper | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | 28 | 30 | total |
| 7 | 7.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6.5 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.002 | 0 | 0 | 0 | 0.002 |
| 6 | 6.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.007 | 0 | 0.002 | 0 | 0 | 0.009 |
| 5.5 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.009 | 0.013 | 0.004 | 0.002 | 0.002 | 0 | 0.029 |
| 5 | 5.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.009 | 0.02 | 0.013 | 0.002 | 0.004 | 0 | 0 | 0.047 |
| 4.5 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0.002 | 0.009 | 0.024 | 0.051 | 0.018 | 0.002 | 0 | 0 | 0 | 0.105 |
| 4 | 4.5 | 0 | 0 | 0 | 0 | 0 | 0.002 | 0.011 | 0.045 | 0.131 | 0.062 | 0.013 | 0.002 | 0 | 0 | 0 | 0.265 |
| 3.5 | 4 | 0 | 0 | 0 | 0 | 0 | 0.011 | 0.084 | 0.253 | 0.189 | 0.055 | 0.013 | 0.004 | 0 | 0 | 0 | 0.607 |
| 3 | 3.5 | 0 | 0 | 0 | 0.002 | 0.018 | 0.147 | 0.498 | 0.596 | 0.235 | 0.025 | 0.007 | 0 | 0 | 0 | 0 | 1.529 |
| 2.5 | 3 | 0 | 0.004 | 0.013 | 0.04 | 0.245 | 1.045 | 1.411 | 0.716 | 0.125 | 0.02 | 0 | 0 | 0 | 0 | 0 | 3.619 |
| 2 | 2.5 | 0.005 | 0.031 | 0.145 | 0.525 | 1.776 | 3.329 | 1.542 | 0.384 | 0.053 | 0.004 | 0 | 0 | 0 | 0 | 0 | 7.793 |
| 1.5 | 2 | 0.045 | 0.322 | 0.982 | 3.009 | 5.067 | 2.907 | 0.736 | 0.129 | 0.027 | 0.002 | 0 | 0 | 0 | 0 | 0 | 13.225 |
| 1 | 1.5 | 0.474 | 2.065 | 4.523 | 7.603 | 4.543 | 1.556 | 0.631 | 0.213 | 0.015 | 0 | 0 | 0 | 0 | 0 | 0 | 21.622 |
| 0.5 | 1 | 2.065 | 6.977 | 9.849 | 7.67 | 4.65 | 1.667 | 0.465 | 0.011 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 33.355 |
| 0 | 0.5 | 2.534 | 6.463 | 6.032 | 2.645 | 0.116 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17.79 |
| total | | 5.125 | 15.861 | 21.544 | 21.493 | 16.416 | 10.664 | 5.379 | 2.356 | 0.807 | 0.247 | 0.084 | 0.015 | 0.007 | 0.002 | 0 | 100 |

(a) Wave Height versus Wind Speed

Wave Period [s]

Wave Height [m]

| | lower | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| lower | upper | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | total |
| 7 | 7.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6.5 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.002 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.002 |
| 6 | 6.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.002 | 0.007 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.009 |
| 5.5 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.002 | 0.015 | 0.013 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.029 |
| 5 | 5.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0.002 | 0.005 | 0.027 | 0.013 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.047 |
| 4.5 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0.002 | 0.047 | 0.044 | 0.013 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.105 |
| 4 | 4.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0.029 | 0.184 | 0.045 | 0.007 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.265 |
| 3.5 | 4 | 0 | 0 | 0 | 0 | 0 | 0.011 | 0.285 | 0.251 | 0.058 | 0.002 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.607 |
| 3 | 3.5 | 0 | 0 | 0 | 0 | 0.002 | 0.245 | 0.998 | 0.256 | 0.027 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.529 |
| 2.5 | 3 | 0 | 0 | 0 | 0 | 0.147 | 2.311 | 1.042 | 0.116 | 0.004 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.619 |
| 2 | 2.5 | 0 | 0 | 0 | 0.035 | 4.138 | 3.42 | 0.189 | 0.013 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7.793 |
| 1.5 | 2 | 0 | 0 | 0 | 4.136 | 8.495 | 0.513 | 0.065 | 0.011 | 0.005 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13.225 |
| 1 | 1.5 | 0 | 0 | 1.949 | 14.349 | 4.412 | 0.789 | 0.102 | 0.013 | 0.005 | 0.004 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21.622 |
| 0.5 | 1 | 0 | 1.912 | 13.264 | 11.531 | 4.508 | 1.411 | 0.404 | 0.124 | 0.073 | 0.045 | 0.033 | 0.02 | 0.011 | 0.013 | 0.002 | 0.004 | 0.002 | 0 | 0 | 0 | 33.355 |
| 0 | 0.5 | 0 | 3.734 | 5.617 | 4.051 | 2.103 | 0.969 | 0.544 | 0.342 | 0.118 | 0.089 | 0.078 | 0.04 | 0.018 | 0.029 | 0.013 | 0.029 | 0.011 | 0.004 | 0.002 | 0 | 17.79 |
| total | | 0 | 5.647 | 20.829 | 34.102 | 23.805 | 9.667 | 3.662 | 1.364 | 0.424 | 0.195 | 0.111 | 0.06 | 0.029 | 0.042 | 0.015 | 0.033 | 0.013 | 0.004 | 0.002 | 0 | 100 |

(b) Wave Height versus Wave Period

Figure B.2: Wave Heigth versus Wind Speed/Wave Period

**Maximum Wave angle for Wave Height - Wave Period data [°]**

| Wave Height [m] \ Wave Period [s] | 2.5 | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 | 11.5 | 12.5 | 13.5 | 14.5 | 15.5 | 16.5 | 17.5 | 18.5 | 19.5 | 20.5 | 21.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **7.25** | 83 | 80 | 78 | 75 | 72 | 70 | 68 | 65 | 63 | 61 | 59 | 57 | 55 | 53 | 51 | 50 | 48 | 47 | 45 | 44 |
| **6.75** | 83 | 80 | 77 | 74 | 71 | 69 | 66 | 64 | 61 | 59 | 57 | 55 | 53 | 51 | 49 | 48 | 46 | 45 | 43 | 42 |
| **6.25** | 82 | 79 | 76 | 73 | 70 | 67 | 64 | 62 | 59 | 57 | 55 | 53 | 51 | 49 | 47 | 45 | 44 | 42 | 41 | 40 |
| **5.75** | 81 | 78 | 75 | 71 | 68 | 65 | 63 | 60 | 57 | 55 | 53 | 50 | 48 | 46 | 45 | 43 | 41 | 40 | 39 | 37 |
| **5.25** | 80 | 77 | 73 | 70 | 66 | 63 | 60 | 57 | 55 | 52 | 50 | 48 | 46 | 44 | 42 | 40 | 39 | 37 | 36 | 35 |
| **4.75** | 80 | 75 | 72 | 68 | 64 | 61 | 58 | 55 | 52 | 50 | 47 | 45 | 43 | 41 | 39 | 38 | 36 | 35 | 33 | 32 |
| **4.25** | 78 | 74 | 70 | 66 | 62 | 58 | 55 | 52 | 49 | 46 | 44 | 42 | 40 | 38 | 36 | 35 | 33 | 32 | 30 | 29 |
| **3.75** | 77 | 72 | 67 | 63 | 59 | 55 | 51 | 48 | 45 | 43 | 40 | 38 | 36 | 34 | 33 | 31 | 30 | 29 | 27 | 26 |
| **3.25** | 75 | 69 | 64 | 59 | 55 | 51 | 47 | 44 | 41 | 39 | 36 | 34 | 32 | 31 | 29 | 28 | 27 | 25 | 24 | 23 |
| **2.75** | 72 | 66 | 60 | 55 | 50 | 46 | 43 | 39 | 37 | 34 | 32 | 30 | 28 | 27 | 25 | 24 | 23 | 22 | 21 | 20 |
| **2.25** | 69 | 61 | 55 | 49 | 45 | 40 | 37 | 34 | 31 | 29 | 27 | 25 | 24 | 22 | 21 | 20 | 19 | 18 | 17 | 17 |
| **1.75** | 63 | 55 | 48 | 42 | 37 | 34 | 30 | 28 | 25 | 23 | 22 | 20 | 19 | 18 | 17 | 16 | 15 | 14 | 14 | 13 |
| **1.25** | 55 | 45 | 38 | 33 | 29 | 25 | 23 | 20 | 19 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 11 | 10 | 10 | 9 |
| **0.75** | 40 | 31 | 25 | 21 | 18 | 16 | 14 | 13 | 11 | 10 | 10 | 9 | 8 | 8 | 7 | 7 | 7 | 6 | 6 | 6 |
| **0.25** | 16 | 11 | 9 | 7 | 6 | 5 | 5 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 |

(a) Maximum Wave Angle for Wave Height - Wave Period data (°)

**Maximum Wave angle per second for Wave Height - Wave Period data [°/s]**

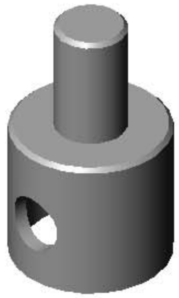
| Wave Height [m] \ Wave Period [s] | 2.5 | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 | 11.5 | 12.5 | 13.5 | 14.5 | 15.5 | 16.5 | 17.5 | 18.5 | 19.5 | 20.5 | 21.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **7.25** | 84.5 | 79.3 | 72.6 | 64.9 | 56.8 | 49.0 | 41.8 | 35.6 | 30.4 | 26.1 | 22.5 | 19.5 | 17.1 | 15.1 | 13.4 | 11.9 | 10.7 | 9.6 | 8.7 | 8.0 |
| **6.75** | 84.1 | 78.5 | 71.4 | 63.3 | 54.9 | 46.9 | 39.8 | 33.7 | 28.6 | 24.5 | 21.1 | 18.3 | 16.0 | 14.1 | 12.5 | 11.1 | 10.0 | 9.0 | 8.2 | 7.4 |
| **6.25** | 83.6 | 77.6 | 70.0 | 61.5 | 52.8 | 44.7 | 37.6 | 31.7 | 26.8 | 22.9 | 19.6 | 17.0 | 14.8 | 13.1 | 11.6 | 10.3 | 9.2 | 8.3 | 7.6 | 6.9 |
| **5.75** | 83.1 | 76.6 | 68.4 | 59.5 | 50.5 | 42.4 | 35.4 | 29.6 | 24.9 | 21.2 | 18.2 | 15.7 | 13.7 | 12.0 | 10.7 | 9.5 | 8.5 | 7.7 | 7.0 | 6.3 |
| **5.25** | 82.4 | 75.3 | 66.6 | 57.1 | 47.9 | 39.8 | 32.9 | 27.4 | 23.0 | 19.5 | 16.7 | 14.4 | 12.6 | 11.0 | 9.8 | 8.7 | 7.8 | 7.0 | 6.4 | 5.8 |
| **4.75** | 81.6 | 73.9 | 64.4 | 54.5 | 45.1 | 37.0 | 30.4 | 25.1 | 21.0 | 17.8 | 15.2 | 13.1 | 11.4 | 10.0 | 8.8 | 7.9 | 7.1 | 6.4 | 5.8 | 5.2 |
| **4.25** | 80.6 | 72.1 | 61.9 | 51.4 | 41.9 | 34.0 | 27.7 | 22.8 | 19.0 | 16.0 | 13.6 | 11.7 | 10.2 | 9.0 | 7.9 | 7.1 | 6.3 | 5.7 | 5.2 | 4.7 |
| **3.75** | 79.4 | 69.9 | 58.8 | 47.9 | 38.4 | 30.7 | 24.8 | 20.3 | 16.9 | 14.2 | 12.1 | 10.4 | 9.0 | 7.9 | 7.0 | 6.2 | 5.6 | 5.0 | 4.5 | 4.1 |
| **3.25** | 77.8 | 67.1 | 55.1 | 43.8 | 34.4 | 27.3 | 21.9 | 17.8 | 14.7 | 12.4 | 10.5 | 9.0 | 7.8 | 6.9 | 6.1 | 5.4 | 4.8 | 4.4 | 3.9 | 3.6 |
| **2.75** | 75.7 | 63.5 | 50.5 | 39.0 | 30.1 | 23.6 | 18.7 | 15.2 | 12.5 | 10.5 | 8.9 | 7.7 | 6.7 | 5.8 | 5.1 | 4.6 | 4.1 | 3.7 | 3.3 | 3.0 |
| **2.25** | 72.7 | 58.6 | 44.7 | 33.6 | 25.4 | 19.6 | 15.5 | 12.5 | 10.3 | 8.6 | 7.3 | 6.3 | 5.5 | 4.8 | 4.2 | 3.7 | 3.4 | 3.0 | 2.7 | 2.5 |
| **1.75** | 68.2 | 51.9 | 37.6 | 27.3 | 20.3 | 15.5 | 12.2 | 9.8 | 8.1 | 6.7 | 5.7 | 4.9 | 4.2 | 3.7 | 3.3 | 2.9 | 2.6 | 2.4 | 2.1 | 1.9 |
| **1.25** | 60.7 | 42.3 | 28.8 | 20.2 | 14.8 | 11.2 | 8.8 | 7.0 | 5.8 | 4.8 | 4.1 | 3.5 | 3.0 | 2.7 | 2.3 | 2.1 | 1.9 | 1.7 | 1.5 | 1.4 |
| **0.75** | 46.9 | 28.6 | 18.3 | 12.5 | 9.0 | 6.8 | 5.3 | 4.2 | 3.5 | 2.9 | 2.5 | 2.1 | 1.8 | 1.6 | 1.4 | 1.3 | 1.1 | 1.0 | 0.9 | 0.8 |
| **0.25** | 19.6 | 10.3 | 6.3 | 4.2 | 3.0 | 2.3 | 1.8 | 1.4 | 1.2 | 1.0 | 0.8 | 0.7 | 0.6 | 0.5 | 0.5 | 0.4 | 0.4 | 0.3 | 0.3 | 0.3 |

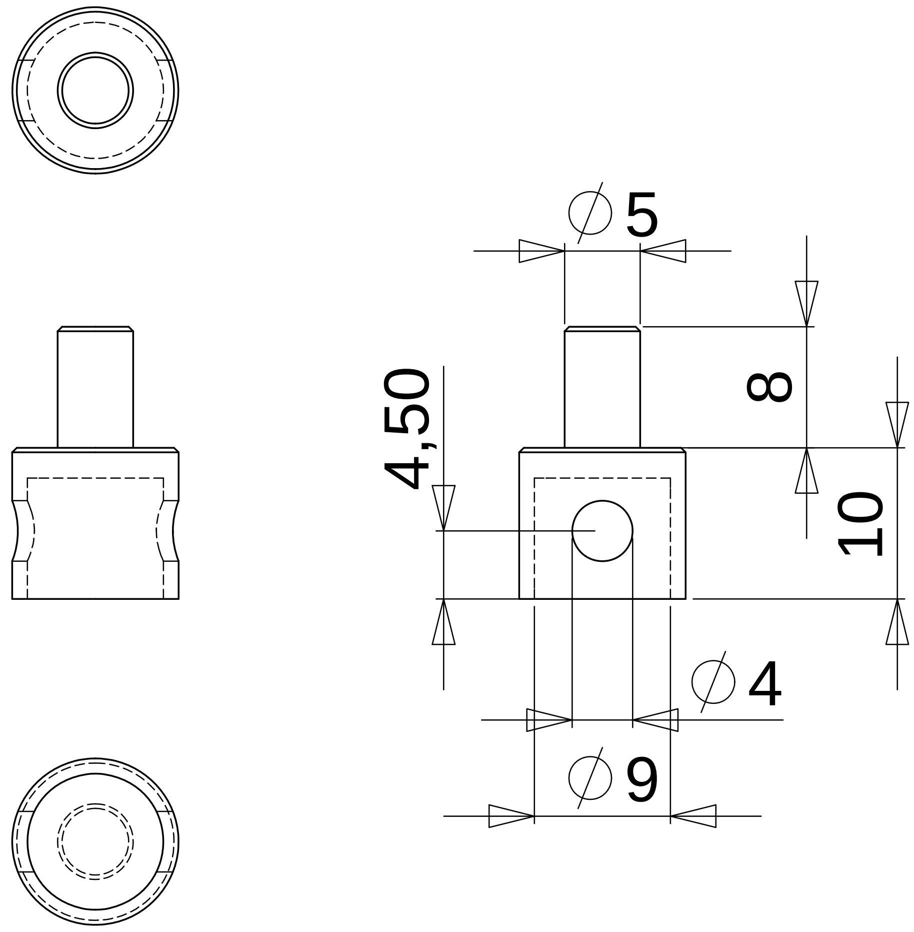
(b) Maximum Wave Angle per Second for Wave Height - Wave Period data (°/$s$)

Figure B.3: Maximum Wave Angle for Wave Heights

# C

# Technical Drawing Linkage Connector






| | | | | |
|---|---|---|---|---|
| TU Delft DCSC | File: verloop motorkoppeling | | date: 6-6-2014 | units: mm |
| | | scale: 2:1 | dep. DCSC | formaat A4 | drawing number: 1.0 |
| | | author: Kees Slinkman | | | |