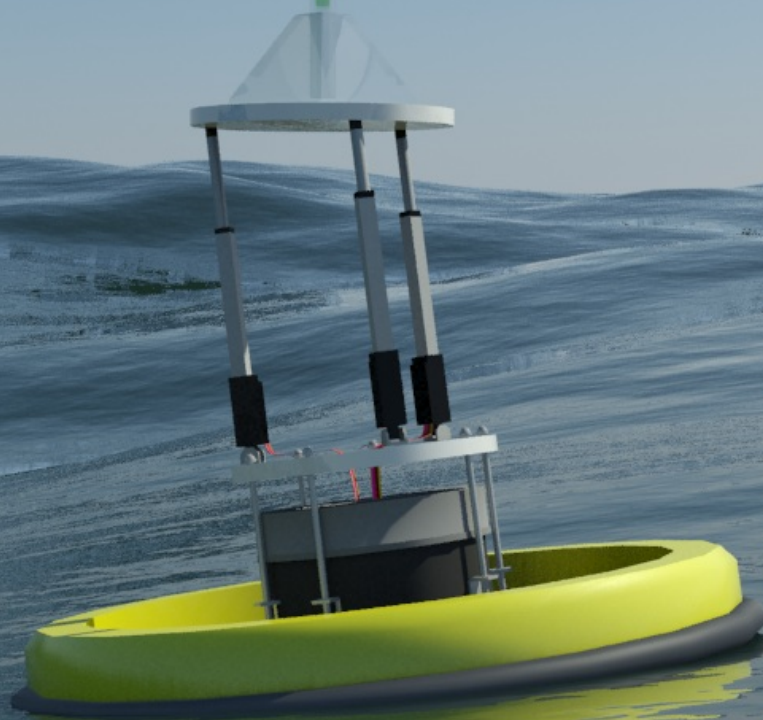


Stabilizing Control System of a Platform on a Buoy for Offshore Wind Assessment

Design Report

J.C. Mes and P.L. de Goffau

Technische Universiteit Delft



STABILIZING CONTROL SYSTEM OF A PLATFORM ON A BUOY FOR OFFSHORE WIND ASSESSMENT

DESIGN REPORT

by

J.C. Mes and P.L. de Goffau

PREFACE

This thesis is written as a part of the bachelor program in Electrical Engineering at the Delft University of Technology. The underlying research is done by the two authors of this thesis, in the framework of a bigger group. This group of six students consists solely of students from the bachelor program in Electrical Engineering at the Delft University of Technology. We would like to thank ir. Sachin Navalkar for reviewing our literature study, thesis and recommendations on our research. We would also like to thank Kees Slinkman for helping us with the assembly of the system and recommendations on materials. We are thankful to the other group members, Mathieu Baas, Tom Hogervorst, Arjan van der Kruijt and Annemieke Pannekoek, for being a huge inspiration. This thesis is judged by Dr. S.D. Cotozana, Ir. S.T. Navalkar and Prof.ir. L. van der Sluis, all connected to the Delft University of Technology.

*J.C. Mes and P.L. de Goffau
Delft, July 2, 2014*

CONTENTS

Summary	vii
1 Introduction	1
1.1 Scope	1
1.2 Goal of the project	1
1.3 Outline of the report	2
2 Requirements and Restrictions	3
2.1 Guidelines	3
2.1.1 Environmental requirements on final buoy	3
2.1.2 Requirements on dimensions of the final buoy	3
2.1.3 Requirements on power consumption of the final buoy	4
2.1.4 Requirements on production and safety of the final buoy	4
2.2 Requirements	4
2.2.1 General Requirements on the prototype	4
2.2.2 Functional Requirements on Stabilization System on Prototype	4
2.3 Restrictions	5
3 Related research	7
3.1 Other buoys using LiDAR for wind measurements	7
3.1.1 Seawatch Wind LiDAR Buoy	7
3.1.2 FLiDAR	7
3.1.3 The Neptune Project	7
3.1.4 WindSentinel	8
3.2 Stabilization Systems	8
3.2.1 Gimbal Stabilization	8
3.2.2 Flywheel stabilization	8
3.2.3 Stabilization with actuators	8
3.3 Implementation of Control Systems	9
3.4 System Identification	9
4 Development	11
4.1 Topology	11
4.1.1 Schematic view	11
4.1.2 Mechanical part	11
4.2 Controller	12
4.2.1 Influence of waves on the buoy	13
4.2.2 Control system	14
4.3 Actuation of sensors and Actuators	14
4.3.1 Sensor control	15
4.3.2 Actuator control	16
4.3.3 Implementation on microcontroller	16
4.4 Validation	17
4.4.1 Cost and Time limitation	17
4.4.2 Buoyancy	18
4.4.3 Maximum tilt at stable position	18
4.4.4 Speed of stabilization system	18
4.4.5 Maximum compensation of angle of tilt	18
4.4.6 Reliability	18
4.4.7 Limitation of the actuator lengths	18
4.4.8 Total system	19

5	Results	21
5.1	Cost and Time limitation	21
5.2	Buoyancy	21
5.3	Maximum angle of tilt at stable position	21
5.4	Speed of stabilization system	21
5.5	Maximum compensation of angle of tilt.	22
5.6	Reliability	22
5.7	Limitation of the actuator lengths.	22
5.8	Total system.	22
6	Conclusion	25
6.1	Evaluation of requirements	25
6.1.1	Cost and Time limitation.	25
6.1.2	Buoyancy	25
6.1.3	Maximum tilt at stable position	25
6.1.4	Speed of stabilization system	25
6.1.5	Maximum compensation of angle of tilt	25
6.1.6	Reliability	26
6.1.7	Limitation of the actuator lengths	26
7	Discussion	27
7.1	Improved microcontroller.	27
7.2	Improved actuators	27
7.3	One additional actuator.	27
7.4	Improved H-bridge	28
7.5	Sensors	28
7.5.1	Kalman filter and a combination of sensors	28
7.5.2	Using only one sensor	28
7.6	Improved length limitation circuit	28
7.7	Improved simulation and derivation of transfer function	28
7.8	Feedforward control system.	28
7.9	Concluding remarks	28
	Bibliography	29

SUMMARY

The purpose of this project is to design a control system to stabilize a platform on a buoy. Stabilization of the platform on the buoy is needed for reliable measurements of wind speed and wind direction on sea using LiDAR (Light Detection And Ranging) modules. These modules use the reflection of particles in the air to measure the wind speed and wind direction. This report is a description of the design of a prototype for a buoy with a stabilized platform. The research contains a study on the behavior of a buoy on waves, a description of the choices made for the design, a description of the used test methods, the test results and some recommendations for improvements on the design, based on the test results. The platform is controlled by three linear actuators of adjustable length. The angle of tilt of the platform is measured with a gyroscope and is used for controlling the linear actuators. The platform is able to compensate an angle of tilt that is smaller than 38° . The reaction time on deviations that are smaller than 10° is less than 1.2 seconds. The reliability on the long term must be improved, through implementation of some recommendations. One of these recommendations is the use of a Kalman filter to prevent long term drift of sensor output by combining different kinds of sensors.

1

INTRODUCTION

1.1. SCOPE

Humankind has always had a need for energy. The expansion of the world demand for energy has been met by ever-increasing exploitation of fossil fuels, oil, natural gas and coal. In 1972, a report for the Club of Rome Project on Predicament of Mankind was published [1]. This report contains a mathematical model of the world with five basic variables: population, capital, food, natural resources and pollution. The biggest challenge for power engineers is how to provide energy for the exponentially growing world population. However, the ongoing expansion of energy demand will be constrained by ecological considerations such as limits to available sites for power stations, heat and water disposal, water availability, air pollution and possible effects on our climate [2]. Therefore new developments in energy conversion have been made. One of these ongoing developments is the conversion of wind energy to electrical energy. Power is generated by turbines that convert the mechanical energy of the wind to electrical energy. To optimize this process, the turbines need to be placed in areas where wind speed is above a given minimum to maintain operation and below a given maximum to ensure safety. Generally, offshore wind conditions are better suited for electricity generation [3]. The history of the development of wind power shows that the increasing demand for energy are met more and more by offshore wind farms [4]. The European Wind Energy Association (EWEA) set a target of 40 GW wind power capacity on offshore wind farms in 2020 [5]. To reach this target, new locations have to be found for these farms. These locations should be determined by reliable wind measurements. This data can be obtained in a couple of ways. One option is to measure the wind speed and direction with meteorological masts. The installation of these masts is expensive, and these masts have a static position. A smarter option is to obtain the wind measurements with buoys equipped with a Light Detection And Ranging (LiDAR) module. There are several companies already exploiting these buoys to obtain wind measurements.

1.2. GOAL OF THE PROJECT

Due to motions of waves the top of the buoy has an angular motion around the x (roll), y (pitch) and z (yaw) axes. These motions are visualized in figure 1.1.

For several buoys the influences of these motions on the wind measurements of the LiDAR module are compensated by software corrections. This has a negative impact on the reliability of this wind data. It would be better to compensate the movement of the LiDAR module with active stabilization. This subject caught the attention of our Bachelor Graduation group at the Delft University of Technology, so a new company is started, called Madaxa [7]. This company will extend the Seawatch Buoy [8] with active stabilization, and will set up a data service for energy companies. This thesis describes the design of the controller of the stabilized platform.

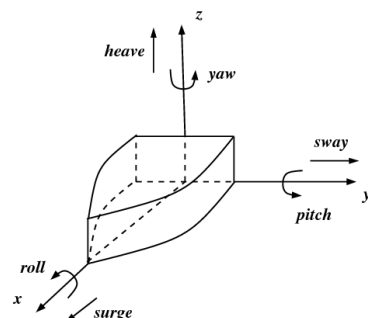


Figure 1.1: Surge, heave, sway, roll, pitch and yaw motions. [6]

1.3. OUTLINE OF THE REPORT

Chapter 2 states the requirements for this controller. After the statement of the requirements, chapter 3 describes other buoys using LiDAR to measure the wind speed, several stabilization methods, implementation of control systems and some theory about system identification. Chapter 4 describes the model that is used for designing the system, a description of the design and the methods of testing. The results on these tests are described in chapter 5. Chapter 6 describes whether the requirements for the design have been met. Chapter 7 describes the recommendations for improving the quality of the product.

2

REQUIREMENTS AND RESTRICTIONS

The following chapter describes the requirements for a stabilizing system on a buoy. The mechanical design of the buoy is described by Mathieu Baas and Annemieke Pannekoek [9]. Tom Hogervorst and Arjan van der Kruijt describe the control system for the position control system [10]. For practical reasons only a scaled model of a buoy is designed. Therefore these theses only describe the design of this prototype. Although this thesis only describes the design of a prototype, it is certainly important to keep the requirements on the final buoy in mind. Because we could not test these requirements, we describe them as guidelines in section 2.1. Section 2.2 states the requirements for the stabilization system. Due to design choices by the other group members there are also some design restrictions. These are described in section 2.3.

2.1. GUIDELINES

This thesis describes the design of a prototype of a buoy with a stabilized platform on top. This section describes the requirements for the final buoy, to keep these requirements in mind when making the design choices for the prototype. First the conditions which the final buoy shall be able to withstand is described in subsection 2.1.1. Subsection 2.1.2 describes the dimensions of the final buoy. Subsection 2.1.3 describes the power requirements for the final buoy. Finally the production and safety requirements on the final buoy are stated in subsection 2.1.4.

2.1.1. ENVIRONMENTAL REQUIREMENTS ON FINAL BUOY

The buoy that has to be designed has to be able to withstand offshore weather conditions at the North Sea. We formulated these conditions as follows:

1. The buoy has to be able to operate in sea water with temperatures above -10° Celsius.
2. The buoy has to be able to operate in offshore weather conditions at the North Sea.
3. The buoy has to be able to operate in a sea with maximal wave heights of 6 m [11].
4. The buoy has to be able to operate in weather conditions with wind speeds up to 40 m/s.

2.1.2. REQUIREMENTS ON DIMENSIONS OF THE FINAL BUOY

The buoy has to have a stabilized platform on which the LIDAR module ZephIR 300 [12] is mounted.

1. The platform on the buoy has to be big enough to carry the ZephIR 300 module. The width and length of the platform shall be greater than 0.25 m.
2. The platform on the buoy has to be strong enough to carry the weight of the ZephIR 300 module which weighs 55 kg.

2.1.3. REQUIREMENTS ON POWER CONSUMPTION OF THE FINAL BUOY

The design of the final buoy and its prototype is based on the Seawatch Buoy from Oceanor [8]. This buoy is equipped with a lithium battery bank with a capacity of 9792 Ah at 12 V and a lead-acid battery bank with a capacity of 248 Ah at 12 V. Furthermore the buoy is equipped with solar panels that can supply 180 W. If we assume a recharging period of 30 days, the average total power that can be consumed is roughly 347.3 W, according to equation 2.1. Because the buoy needs a lot of this power for the communication with the base station, more power is needed. We assume that the power that is used by the buoy is approximately 180 W, because Fugro Oceanor chose this amount of solar power. That implies that there is approximately 170 W power left. The remaining power is divided by the stabilization system for the platform, and the propulsion system for the autonomous position control, designed by Tom Hogervorst and Arjan van der Kruijt [10]. There is enough space for more solar panels, so if more power is needed, more solar panels could be added.

$$\frac{(9792[Ah] + 248[Ah]) \times 12[V]}{30 * 24[h]} + 180[W] = 347.3[W] \quad (2.1)$$

1. The buoy has to be able to operate for 30 days after it has been fully charged.
2. The stabilization system has to use less power than 70 W on average.
3. The position control system has to use less power than 100 W on average.

2.1.4. REQUIREMENTS ON PRODUCTION AND SAFETY OF THE FINAL BUOY

1. The buoy has to be produced such that all components are easily replaceable.
2. 70% of the components of the buoy have to be recyclable.
3. The production costs of the buoy should not exceed € 50000.
4. The buoy has to comply with the European regulations concerning the environment, recycling and safety.

2.2. REQUIREMENTS

Subsection 2.2.1 describes the general requirements on the prototype of the buoy. The functional requirements are described in subsection 2.2.2.

2.2.1. GENERAL REQUIREMENTS ON THE PROTOTYPE

1. The prototype has to float and retain its vertical position.
2. The cost of the material of the prototype should not exceed € 800.
3. The prototype has to be built in two months.
4. The prototype has to be a scaled model of the final buoy, with a scaling factor of 5, to make it easier to fabricate in a lab.

2.2.2. FUNCTIONAL REQUIREMENTS ON STABILIZATION SYSTEM ON PROTOTYPE

On the prototype a platform will be mounted that has to be stabilized with a stabilizing controller. The requirements on this controller are as follows:

1. The maximum allowed degree of tilt of the platform has to be 5° with respect to the horizon, in the direction of roll and pitch (for the definition of these motion see figure 1.1).
2. If the degree of tilt is greater then the maximum allowed tilt of 5° with respect to the horizon, the reaction time of getting back has to be smaller than 1 s, because the period of waves at the North Sea is approximately 5 seconds.
3. The controller has to be able to compensate a maximum degree of tilt of 35° with respect to roll and pitch (for the definition of these motions, see figure 1.1).

4. The control system must be reliable for 30 days. Calibration may be needed at the start of this period, but during this time period further calibration should not be needed.
5. The movement of the actuators will be limited in such a way that the linear motor stops when the minimum or maximum length is reached, to prevent damage to the actuators.

2.3. RESTRICTIONS

Due to design choices of Mathieu Baas and Annemieke Pannekoek [9] the following restrictions are stated:

1. The electrical components of the prototype have to be mounted in a water resistant box.
2. The prototype will have a limited waterproof space reserved for electrical components, to ensure water resistance. This space has a cylindrical form, with a radius of 0.1 m and a height of 0.3 m.
3. The sensors that are used for the measurement of the pitch and roll angles are 3-axis gyroscopes, manufactured by Parallax, with type number L3G4200D [13].
4. The actuators that provide the desired compensation motions are manufactured by Firgelli, with type number L16-100-63-12-P. They have a minimal length of 12 cm, a maximal length of 22 cm and an accuracy of 0.4 mm [14].
5. The power source that must be used for the design delivers +3.3 V, +5 V and +12 V.

3

RELATED RESEARCH

In order to meet the requirements stated in section 2, this chapter describes the research, that has already been done by others in the field of offshore wind measurements with buoys using LiDAR, stabilization systems and the implementation of control systems.

3.1. OTHER BUOYS USING LiDAR FOR WIND MEASUREMENTS

This section describes similar buoys obtaining wind measurements with LiDAR.

3.1.1. SEAWATCH WIND LiDAR BUOY

The first buoy described is the Seawatch Wind LiDAR Buoy from Fugro Oceanor [8]. This is a moored wavescan buoy mounted with a LiDAR module. It can measure wave properties, such as wave height and wave length, and wind speeds using the ZephIR 300 module. In 2012 wind data from this buoy was compared to wind data retrieved with a mast placed on land, in Norway. The average deviation in wind speed measurements between the Wind LiDAR Buoy and the reference stations was less than 2%. It can measure the wind speed and direction at heights up to 300 m. This buoy is the starting point of the design, because the small size of the lower part of this buoy allows reliable wave measurements. See figure 3.1 for a picture of this buoy.



Figure 3.1: The Seawatch buoy at sea [15]

3.1.2. FLiDAR

FLiDAR is a floating LiDAR based measurement device designed for the harshest offshore conditions developed jointly by Offshore Wind Assistance (OWA, a subsidiary of DEME) [17] and 3E [18]. It has been successfully tested and validated in both North Sea and Irish Sea conditions (15 km offshore). FLiDAR has an offshore WINDCUBE v2 LiDAR mounted on an industry standard buoy and is powered by autonomous renewable energy systems (PV + wind). A mechanical stabilization unit and advanced correction algorithms must ensure maximum data accuracy [19]. It can measure the wind speed and direction at heights up to 200 m. This buoy does not have the ability to measure wave properties. The water depth at which this buoy could be used is 5 to 50 m. See figure 3.2 for a picture of this buoy.



Figure 3.2: The Flidar buoy at sea [16]

3.1.3. THE NEPTUNE PROJECT

One of the more recent developments is the Neptune Project [21]. The goal of this project is to provide a measurement system for both wind and wave data on a moored buoy. For the wind measurements the LiDAR module ZephIR 300 is used [22]. The final design should contain a mechanical motion compensation frame [23]. The project is scheduled to finish at the end of 2014 and the consor-



Figure 3.3: The Neptune buoy at sea [20]

tium expects to start up the commercialized buoy from 2015 on. See figure 3.3 for a picture of this buoy.

3.1.4. WINDSENTINEL

Axys Technologies has developed a wind resource assessment buoy called WindSentinel. This buoy is a combination of the NOMAD buoy, with a Vindicator III LiDAR module mounted on it [25]. The NOMAD buoy has a wide range of sensors for monitoring meteorological, oceanographic and water quality parameters. The buoy can measure the wind speed and direction between 30 to 150 meters vertically with a wind speed range of 0-90 m/s [26]. The LiDAR module is not stabilized. To improve the accuracy a LiDAR module that makes use of sequential pulses is used and the captured data is post processed with software [25]. The buoy has the form of a vessel, to make it easier to displace the buoy. See figure 3.4 for a picture of this buoy.

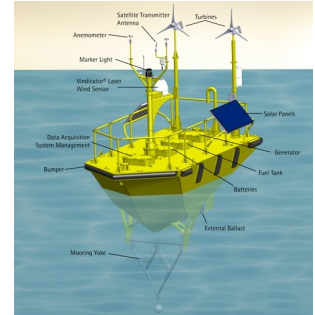


Figure 3.4: The WindSentinel buoy at sea [24]

3.2. STABILIZATION SYSTEMS

This section describes several principles for stabilizing angular motions.

3.2.1. GIMBAL STABILIZATION

Gimbals have often been used for stabilization of cameras. A gimbal is a mechanical device that consists of multiple orthogonal axes. Each axis can rotate freely, controlled with a belt or a chain, such that the orientation of one of these axes can be kept stable in the dimension of the number of axes [27]. Figure 3.5 visualizes the configuration of this stabilization method.

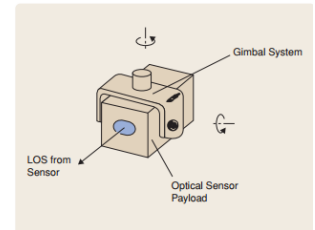


Figure 3.5: A visualization of a gimbal stabilization system [27]

3.2.2. FLYWHEEL STABILIZATION

Another method that can be used for stabilizing the head of the buoy is a gyroscopic stabilizer based on the rotational moment of a spinning flywheel [28]. The angular motion of the flywheel causes a fixed position of the axis, due to the centripetal force. One of the drawbacks of this system is the maintenance that will be needed due to wear, because the stabilization is achieved by continual moving parts. Another drawback of this system is that it is a passive stabilization method, although it has moving parts. There is no feedback loop, so it cannot be guaranteed that the angle of tilt approaches zero.

3.2.3. STABILIZATION WITH ACTUATORS

The last stabilization system described uses linear actuators. In this design the system is split up in two parts. One part of the buoy floats on the waves, and has angular motions caused by the waves. The upper part of the buoy is connected to the bottom part with linear actuators. The number of actuators defines the degrees of freedom of the upper part [29]. Figure 3.6 shows the design of a system that can be controlled in three directions: pitch, roll and heave. This setup is chosen by Mathieu Baas and Anne-mieke Pannekoek because this stabilization technique meets the requirements the best. This active stabilization technique is easy scalable and gives the most flexibility in use.

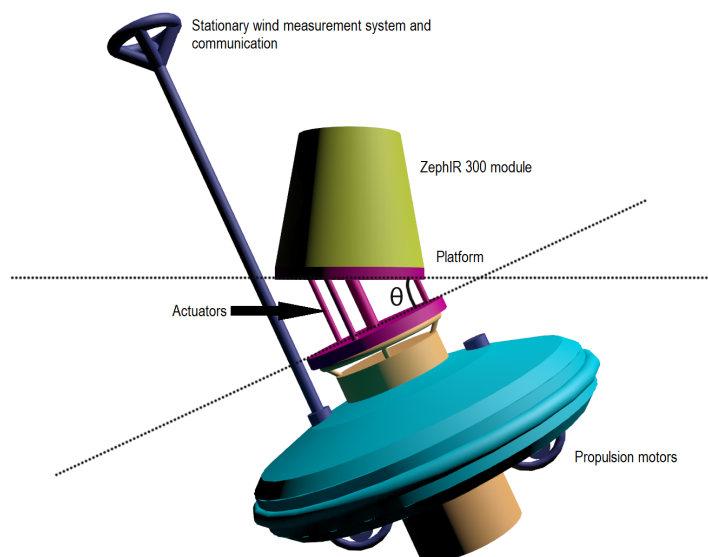


Figure 3.6: A visualization of the stabilization design with actuators

3.3. IMPLEMENTATION OF CONTROL SYSTEMS

Every stabilization configuration will need a control system. The most convenient implementation of a control system is a digital controller, because this method has a high flexibility of use. A digital controller can be implemented on various levels of abstraction and effort. On the lowest level we find the FPGA based approach [30]. This approach has lower delay compared to higher level implementations and allows for more complicated control schemes, but requires more effort in the design process compared to higher level approaches.

On a higher level a microcontroller in combination with an assembly language can be used. In general, the delay caused by the slower microcontroller approach can be estimated in the microsecond scale: an imaginary microcontroller running at $f = 10\text{MHz}$ executes 1000 cycles required for a control loop iteration at $t = (1/f) \times 1000 = 100\mu\text{s}$. This is not a problem on the timescale of the wave disturbance we need to compensate for which can be measured in the 1Hz scale [31]. This arguably makes a microcontroller a better choice: we do not need the advantages of an FPGA build.

On an even higher level we find "high level programming languages" like C++ [32], also in combination with a microcontroller. These languages can be used to write controller code with more ease than the lower level approaches. However, it is only possible to make use of high level languages for which a compiler is available that translates it to the assembly language the microcontroller can execute. An example is AVR-GCC [33] which converts the high level language C code to AVR assembly code.

An example PID implementation example that makes use of pseudocode can be found here [34]. Another paper describes the implementation of a controller using C++ [35].

3.4. SYSTEM IDENTIFICATION

To be able to design a proper controller we need more information about the system that the controller will control. This system can be described using either a transfer function using single-input-single-output (SISO) models, or a more elaborate state space description that supports multiple-input-multiple-output (MIMO) systems in case more than one input or output is needed. Maritime objects can be described using the 6DOF model described in [36]. In this case, only compensation for rotation around the horizontal axes (roll and pitch) is needed, compensated by at least two active parts. This means that at least two state variables and at least two inputs (motor control) are needed. In other words, this system is a MIMO system, and needs to be described using a state space model.

This state space model can be derived from the Lagrangian equation for maritime objects described in [36] and more specifically for buoys in [37], or system identification algorithms which compute systems given input and output values. To make use of the second option, the buoy needs to be fed with a series of known input signals for which the output variables are captured. This data can then be fed to MATLAB functions like `n4sid` [38] which can numerically estimate the system from the input and output data. This function allows for the use of three different estimation algorithms called CVA [39], MOESP [40] and SSARX [41].

The second option (numerical estimation) has the advantage of being easy to execute if there is access to a physical model of the buoy itself, but cannot be used if there is not one. The more accurate Lagrangian method (if the parameters are known) does not suffer from this drawback. Furthermore, being a symbolic equation, it can be easily adapted to changes in the buoy by changing parameters: a rerun of the input/output capture is not needed. Derivation of the Lagrangian is much more difficult though.

Because both methods, numerical estimation and derivation of the Lagrangian, are too difficult to complete within the limited period of time of two months, a third alternative is used, namely a heuristically tuned control system based on an unknown system response. It is unknown how the system behaves due to a certain input, and control system output is linearly calculated based on system output (roll and pitch).

4

DEVELOPMENT

This chapter describes the design choices, the algorithms used for the controller and the methods of validation of the design. Section 4.1 describes the design of the topology of the stabilization unit. Section 4.2 describes the design of the control system. Section 4.3 describes the control of the sensors and the actuators. Section 4.4 describes the methods of testing.

4.1. TOPOLOGY

This section describes the topology of the stabilization unit. First the overall design of the system and the design principles is described in subsection 4.1.1. The design of the mechanical part, done by Mathieu Baas and Annemieke Pannekoek [9], is summarized in subsection 4.1.2.

4.1.1. SCHEMATIC VIEW

Figure 4.1 shows a 3D representation of the topology of the design. The gray plane represents the lower part of the buoy that is affected by the ocean waves. The green plane represents the platform that has to be stabilized. Both parts are connected with three actuators of adjustable length. On both parts of the buoy a sensor is mounted that measures the angle of tilt in two directions (pitch and roll). The upper sensor is meant for observation whether the platform has been controlled the right way, and determines the configuration of the actuators. The lower sensor can be used for observation whether the actuators have been configured the right way.

The output of the sensors is sent to a microcontroller at a given fixed frequency of 32Hz. On this microcontroller a control system is implemented, which accepts the sensor output as its input. The outputs of this control system are sent to the actuators. The length of these actuators can be changed, which influences the angle of the upper platform. The microcontroller is able to increase or decrease the length of each actuator separately, but cannot directly set the length of any actuator. The sensors are further described in section 4.3.1, as well as the control system in section 4.2.2, the microcontroller in section 4.3.3 and the actuators in section 4.3.2.

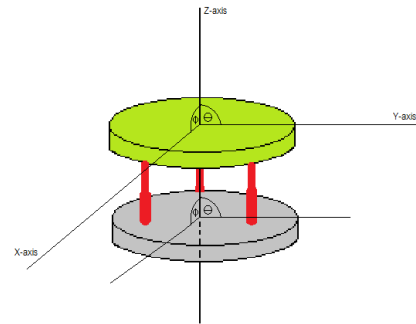


Figure 4.1: A schematic representation of the system, with two tilt measurements

4.1.2. MECHANICAL PART

MECHANICAL DESIGN OF THE LOWER PART OF THE BUOY

To ensure that the buoy is buoyant, as stated in the requirements, the buoy must have enough upward force, and must be waterproof. According to equation 4.1 the volume inside the buoy must be big enough to overcome the mass of the buoy. ρ represents the mass density of water, g the gravitational constant and V represents the volume of air inside the buoy. This force is equal to the gravitational force, which is stated in equation 4.2, where g represents the gravitational constant and m the mass of the buoy. 'A body wholly or partially submerged in a fluid is buoyed up by a force equal to the weight of the displaced fluid.' [43] This principle is known as the Archimedes' principle, and is visualized in figure 4.2.

To ensure enough volume to compensate the mass of the buoy, the buoy contains one hollow cylinder with a wider cylinder mounted on it, visualized in figure 4.3. The sand colored cylinder is the cylinder in which all the electronics can be mounted. This is the space which has been described in the restrictions (section 2.3). The blue cylinder is the part of the buoy that must ensure the buoyancy.

$$F_s = \rho \times g \times V \quad (4.1)$$

$$F_g = m \times g \quad (4.2)$$

MECHANICAL DESIGN OF THE PLATFORM

As stated earlier, the upper and lower part of the buoy are connected by three adjustable actuators, visualized in figure 4.5. The configuration of the lengths of these rods determine the tilt of the platform. The rods are connected to the lower platform with a hinge and with a ball and socket joint to the upper part. This way the platform is only able to move in two directions, namely pitch and roll, which are the requirements on this platform. In principle, to control the platform in two directions two actuators are needed. A design with two actuators should contain one fixed rod, with two orthogonal actuators placed beside. A 2D representation of such a system is visualized in figure 4.4. However, a system with two actuators is not very stable. This system setup would cause high forces on the actuators due to the non uniform distribution of the space of the platform. For that reason a more symmetric setup is chosen with three actuators. More actuators are also considered. For instance, with four actuators the design of the control system could be orthogonal.

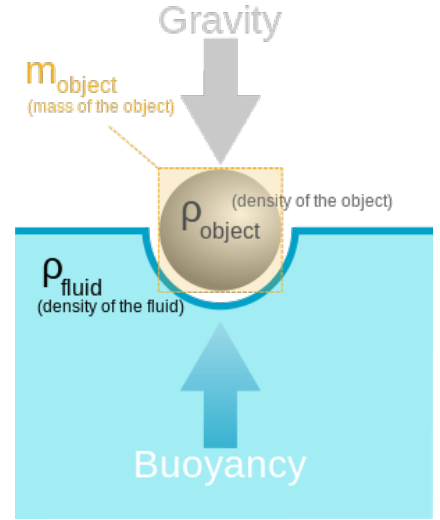


Figure 4.2: A visualization of the Archimedes' principle [42]

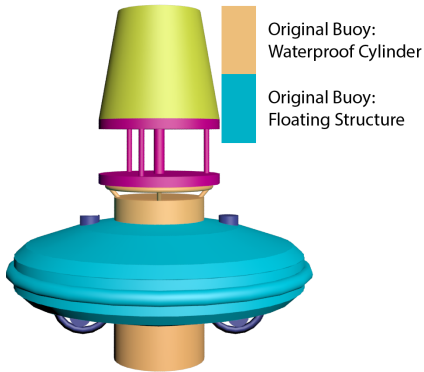


Figure 4.3: A 3D representation of the buoyancy system

However, each additional actuator results in higher costs of the system. For that reason a setup with three actuators has been chosen. The hinges prevent the platform from overturning. If the hinges are not enough to protect the platform from overturning, a fixed rod can be mounted in the middle of the platform, connected with a ball and socket joint to the upper platform. This will keep the middle of the platform fixed, such that the platform is protected against overturning. A fixed rod in the middle could however cause damage to the actuators, because the actuators could experience forces from the other actuators, due to the fixed nature of the platform.

4.2. CONTROLLER

This section describes the design of the control system. It is important to identify first how the buoy behaves in the environment that is

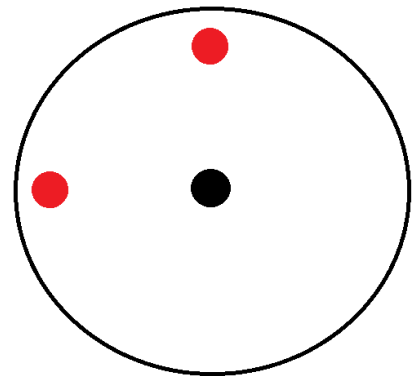


Figure 4.4: A 2D top view of a system with two actuators, indicated as red dots, the fixed rod as a black dot.

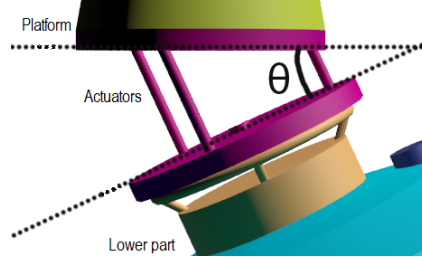


Figure 4.5: A 3D representation of the platform

specified in the requirements. Subsection 4.2.1 describes the model that is used to obtain this behavior. After the behavior of the buoy has been made clear, subsection 4.2.2 describes the control system and its concepts.

4.2.1. INFLUENCE OF WAVES ON THE BUOY

To make the behavior of the platform clear, a simulation has been run in MATLAB. This simulation is based on a model obtained by Thor I. Fossen [36]. The goal of the simulation is to find the linear and angular motion due to linear and angular forces on the buoy caused by waves. For simplicity we estimate the buoy behaviour using a spherical model for the inertia tensor of the buoy. Equation 4.3 is a set of 6 DOF dynamic equations of motion.

$$\dot{v} = -M^{-1}vC_{coriolis} + M^{-1}\tau \quad (4.3)$$

In the model used, matrix M is the rigid body inertia matrix of the buoy. Equation 4.4 shows the entries of the matrix. The rigid body inertia tensor is displayed in equation 4.5. The $C_{coriolis}$ (equation 4.6) matrix contains the Coriolis and centripetal terms. Parts of the M and $C_{coriolis}$ matrices make use of a function $S(\lambda)$ that returns a skew symmetric matrix based on an input vector λ . v (equation 4.8) represents the state vector of the system, containing the position and the orientation of the buoy. \dot{v} represents the change of the state vector. τ is the input vector, that represents the angular torques from the waves on the buoy. In this simulation only angular motion around the axes are of importance. Figure 4.6 shows the simulation result.

$$M = \begin{bmatrix} mI_{3 \times 3} & -mS(r_G) \\ mS(r_G) & I_0 \end{bmatrix} = \begin{bmatrix} m & 0 & 0 & 0 & mz_G & -my_G \\ 0 & m & 0 & -mz_G & 0 & mx_G \\ 0 & 0 & m & my_G & -mx_G & 0 \\ 0 & -mz_g & my_G & I_x & -I_{xy} & -I_{xz} \\ mz_G & 0 & -mx_G & -I_{yx} & I_y & -I_{yz} \\ -my_G & mx_G & 0 & -I_{zx} & -I_{zy} & I_z \end{bmatrix} \quad (4.4)$$

$$I_0 = \begin{bmatrix} (2/5)mr^2 & 0 & 0 \\ 0 & (2/5)mr^2 & 0 \\ 0 & 0 & (2/5)mr^2 \end{bmatrix} \quad (4.5)$$

$$C_{coriolis} = \begin{bmatrix} 0_{3 \times 3} & -mS(v_1) - mS(v_2)S(r_G) \\ -mS(v_1) + mS(r_G)S(v_2) & -S(I_0v_2) \end{bmatrix} \quad (4.6)$$

$$S(\lambda) = \begin{bmatrix} 0 & -\lambda_3 & \lambda_2 \\ \lambda_3 & 0 & -\lambda_1 \\ -\lambda_2 & \lambda_1 & 0 \end{bmatrix} \quad (4.7)$$

$$v = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} v_x \\ v_y \\ v_z \\ v_\theta \\ v_\phi \\ v_\psi \end{bmatrix} \quad (4.8)$$

Input vector τ contains the forces and torques on the buoy. This vector is the input for the simulation. Because only the angular motions are of interest, the linear forces are considered to be zero. The entered

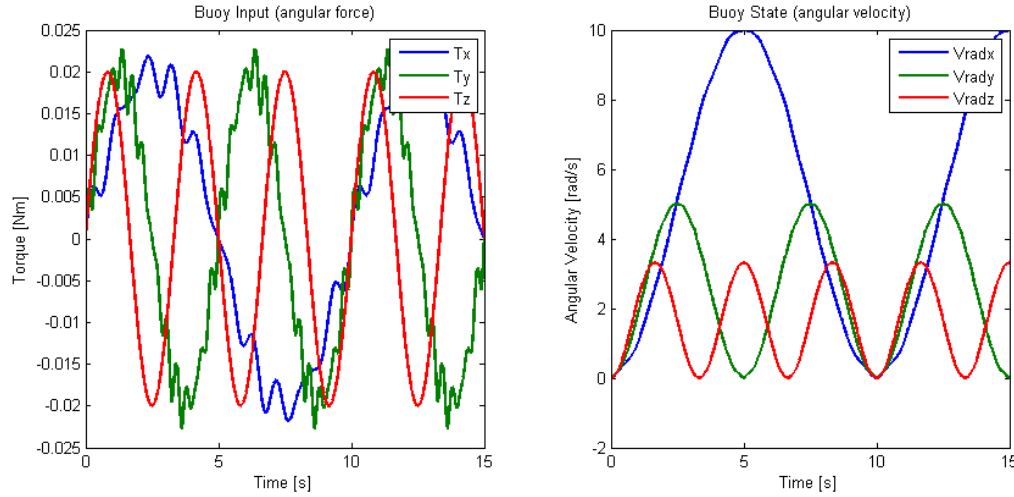


Figure 4.6: A simulation of the reaction of the buoy on angular torques

angular torques have a sinusoidal form. The frequency of the carrier wave is determined using wave data from the North Sea [44]. This document contains wave data from measurements and simulations. The frequencies that occur most frequently are in the region of 0.1-0.3 Hz. These frequencies are used for the carrier waves in the simulation. On these waves small ripples with smaller amplitude and higher frequencies are added. The result of the simulation shows that the influence of ripples, small waves with high frequencies and lower amplitudes compared to the carrier wave, on the angular motions of the buoy is very low. This justifies the assumption that the angular motions of the buoy are only in the order of the carrier frequency of the waves.

4.2.2. CONTROL SYSTEM

In subsection 4.2.1 it is shown that the angular motions of the buoy can be considered as sinusoidal motions with frequencies in the order of the carrier waves, commonly in the order of 0.1-0.3 Hz. Because higher frequencies can be ignored, a complex control system is not needed. If higher frequencies could not be ignored, the control system should contain differential feedback, as well as an integrator. Because the control system only has to deal with low frequencies, such a complex system is not needed, a proportional gain-only system is sufficient. Because the speed of the actuators is relatively low, it is chosen to control the actuators always at maximum speed. The control system therefore only controls whether the actuators must go up, down, or stay stationary. The angles of the sensors must be neutralized by the right configuration of the actuators. Table 4.1 contains the configuration of the actuators at certain inputs of the gyroscope. The first two columns show the angles from the gyroscopes, with a minus sign for negative angles, and a plus sign for the positive angles. The last three columns show the configuration for the actuators for a certain sensor input. A plus sign indicates that the actuator must increase its length, for a minus sign the actuator must decrease its length, and for a 0 the actuator must keep its length. The orientation of the system is visualized in figure 4.7.

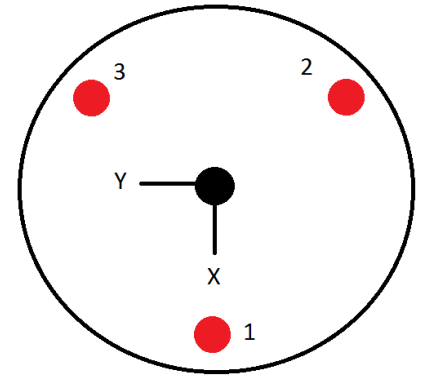


Figure 4.7: A 2D top view of a system with three actuators, indicated as red dots, along as the orientation of the axis.

4.3. ACTUATION OF SENSORS AND ACTUATORS

In section 4.1.1 the structure of the system is already stated. Figure 4.8 shows a schematic view of the structure of the system. For the sensors two gyroscopes are used. These gyroscopes measure the motions around the x (roll), y (pitch) and z (yaw) axis. The properties of these gyroscopes are described in section 4.3.1. Both gyroscopes are connected to the microcontroller using I²C. On the microcontroller the control system as described in sections 4.2.2 and 4.3.3, is implemented. The microcontroller controls the output to the actuators.

roll	pitch	actuator1	actuator2	actuator3
-	-	+	0	-
-	0	0	+	-
-	+	-	+	0
0	-	+	-	-
0	0	0	0	0
0	+	-	+	+
+	-	+	-	0
+	0	0	-	+
+	+	-	0	+

Table 4.1: The control signals for the actuators for all combinations of the angle measurements around the x and y axis.

The actuators are linear motors, controlled with DC voltages. The microcontroller and the actuators are connected through H-bridges. These H-bridges provide the desired high power voltages on the actuators based on low power inputs from the microcontroller. This is further described in section 4.3.2. Because the motors of the actuators must be prevented from slipping, their minimum and maximum lengths must be limited. This is done using 6 comparators, of which the output is sent to the microcontroller.

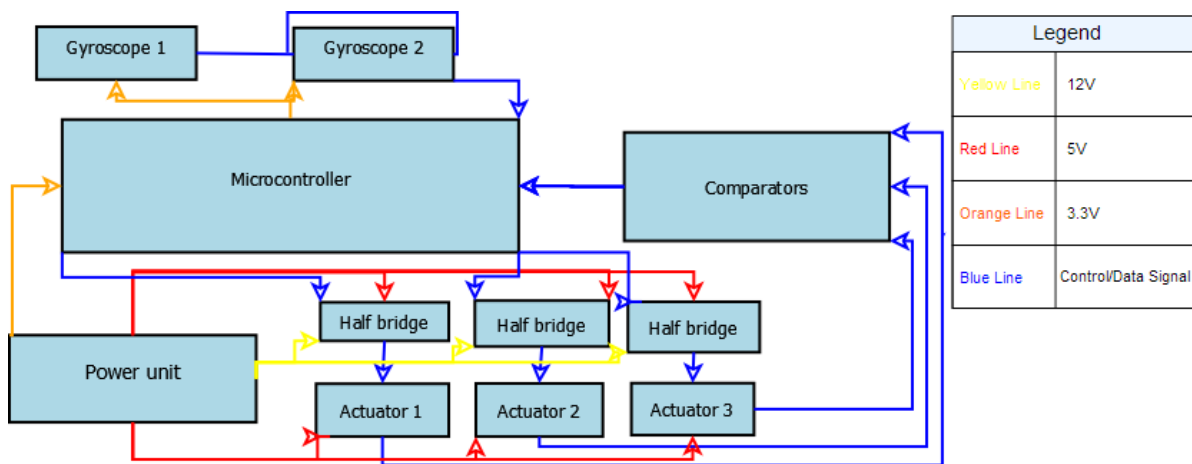


Figure 4.8: A schematic representation of the stabilization system

4.3.1. SENSOR CONTROL

As stated in the restrictions in section 2.3 the sensors that measure the angles are gyroscopes manufactured by Parallax with type number L3G4200D. Figure 4.9 shows a picture of the used gyroscope.

CALIBRATION

In fact these gyroscopes do not measure the angular position, but the angular velocity. To determine the angle of the platform this angular velocity must be integrated, or summed with a Riemann sum. To obtain the right angle, the zero point of gyroscope must be known. The prototype of the buoy must be put on a stable flat surface. Subsequently, the actuators must be controlled so that they have equal lengths. It turns out that gyroscopes have a nonzero noise density, with a mean value that is not equal to zero. This means that a summation of velocities that should result in a stationary angular position would result in a nonzero value. To prevent the summation of noise, some calibration is needed. To achieve this, the zero rate level must be calculated and subtracted from each subsequent measurement. To calculate this value, the sensors are held stationary and their total angle is read after a set period of time. Afterwards, the error per measurement is derived by dividing the total

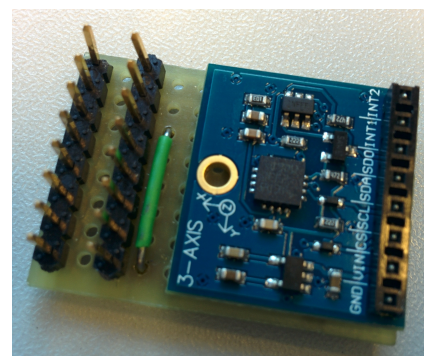


Figure 4.9: A picture of the gyroscope from Parallax

by the amount of readings (it is the cumulative moving average). This value is subtracted from each future measurement, such that the measured stationary velocity will be zero, on average.

INTERLINKING BETWEEN SENSORS

For optimal control two sensors are used, one at the platform and one on the lower part of the buoy. These sensors measure the tilt in three directions (roll, pitch and yaw). The output of the sensors is sent through I²C. Both sensors are coupled at the same output pins at the microcontroller. Each gyroscope has its own identifier, such that the microcontroller can alternately communicate with two gyroscopes on the same wire. The communication through I²C is described in a I²C manual from NXP [45]. The gyroscopes are in succession read out with a frequency of 32 Hz.

4.3.2. ACTUATOR CONTROL

This section describes the design of the circuit between the actuators and the microcontroller. This circuit must transform the +3,3V outputs of the microcontroller to a +12 V or -12 V signal for the actuators. It must also ensure that the actuators will stay in the right region.

VOLTAGE CONTROL

First the circuit is described that transforms the digital signals from the microcontroller to control signals for the actuators. The length of the actuators decreases when the actuators are fed with a negative voltage, and increases when the actuators are fed with a positive voltage. The higher the absolute voltage that is fed to the actuator, the faster the actuator will change its length. Because the actuators must react as fast as possible, it is chosen to always feed the actuator with the highest absolute voltage that the power circuit can deliver. Because the microcontroller only delivers low power signals, an amplifier called a H-bridge that accepts positive and negative voltages is used to supply a high power signal to the actuators. Figure 4.10 shows a picture of one of the circuits. Each IC contains two H-bridges, so two circuit boards have been used, because each of the three actuators needs one H-bridge.

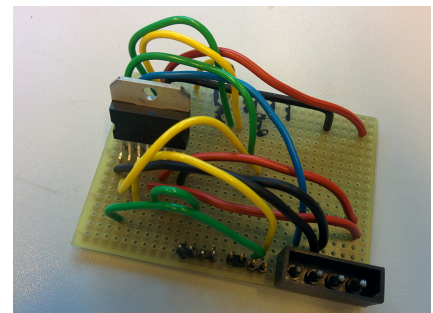


Figure 4.10: A picture of the H-bridge circuit

POTENTIAL LIMITATION

The second circuit that is needed is the circuit that must control the range of the actuators. Each actuator transmits an analogue signal that indicates the length of the actuator. When the actuator has the shortest possible length, the output of this signal is 0.0V. When the actuator has the maximal length, its output is equal to the supply voltage, in our case 5.2V. Figure 4.11 shows a schematic representation of the electrical circuit. The potential input from the actuators is compared with two referential levels. Therefore we use 6 comparators, 3 connected with a 4.8V point, and 3 with a 0.2V point. The outputs of the comparators are low when the lengths of the actuators are within the limits. The comparators that are used are the LM339N differential comparators from Texas Instruments [46]. The outputs of the comparators are connected with the microcontroller. The outputs of the comparators are also connected with a pull-up resistor to the supply voltage. This is because the output would be floating without these resistors.

4.3.3. IMPLEMENTATION ON MICROCONTROLLER

At this point of the design all hardware is designed. The last design step that is left is the design of the control system on the microcontroller. First we have to choose a right type of microcontroller.

MICROCONTROLLER CHOICE

The practicum assistant from the course 'Computer Architecture and Organization' at the Delft University of Technology was willing to lend us a microcontroller. The department had two boards available. One of these contained the AVR ATmega8 controller from Atmel [47]. The other option was the ARM Cortex M3 based LPC1343 microcontroller on an Olimex development board [48]. The AVR option

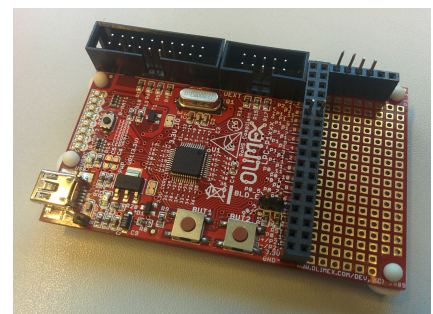


Figure 4.12: A picture of the LPC1343 microcontroller

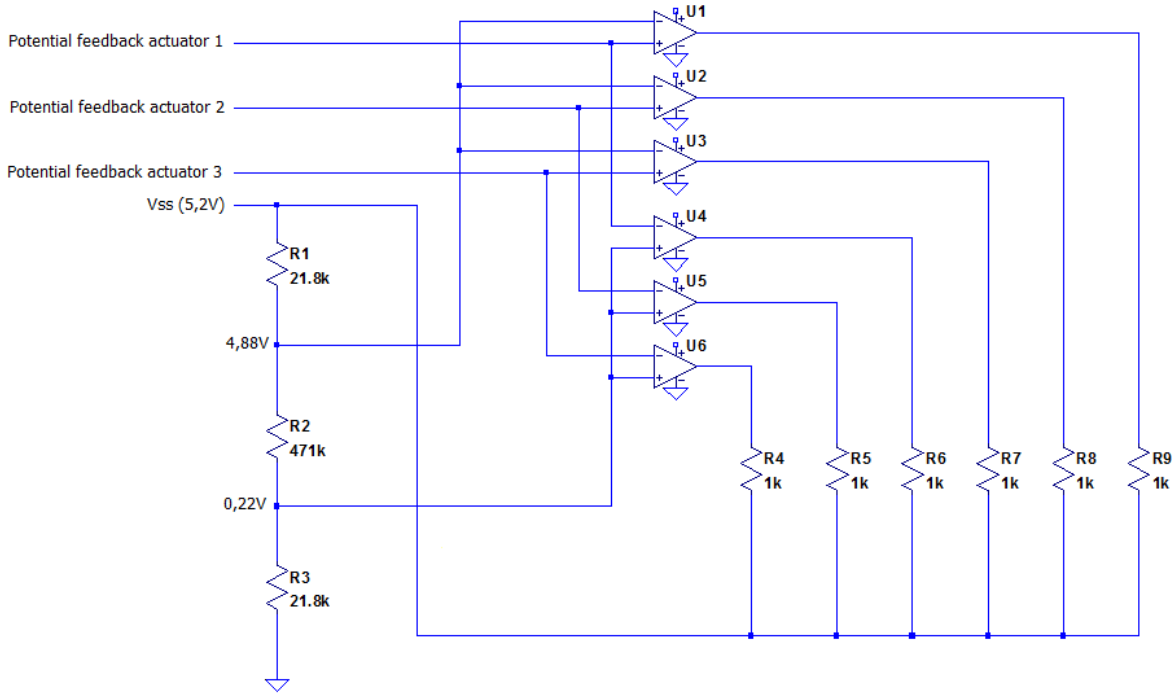


Figure 4.11: A schematic representation of the limitation circuit.

can only process 8bit values per instruction, while for 32bit values at least four times as much instructions (and therefore time) are needed. The ARM option does not have this drawback. Furthermore, the ARM option has a 32bit hardware divider and a 32bit single cycle multiplier. Both features reduce the time needed to perform these operations on 32bit values by hundreds of times compared to AVR according to assembler output produced by AVR and ARM compilers. Due to the limitations of the 8 bit instruction set and the limited size of programs that can be run on the AVR option, the ARM option was chosen. A picture of the ARM microcontroller board is shown in figure 4.12.

CODE REVIEW

The program that is executed by the microcontroller after a reset starts with initializing the actuators. This step ensures that all the actuators are of equal length when the calibration of the sensors starts, so that the initial position value reported by the sensor is zero. When the actuators are initialized, communication is started with the gyroscopes. The data stream for this communication is further described in the manual for I²C from NXP [45]. After communication has been set up, the gyroscopes are calibrated, as described in section 4.3.1. After these calibrations the control system is started. Each time both gyroscopes are read (repeated at 32Hz), the current angle is calculated by summing the velocities that the gyroscopes provide. To further reduce noise, a moving average filter is applied to the gyroscope outputs before they are summed. This reduces high frequency noise. When the current angle has been calculated, the actuator control values are retrieved from table 4.1. The gyroscope on the lower part of the buoy is also read out, but this value is only used for test purposes.

4.4. VALIDATION

This section describes the methods of testing. Section 2.2 states the requirements for the prototype.

4.4.1. COST AND TIME LIMITATION

The requirements on the costs and the time could not be measured. For the total costs the costs for each component should be added, and compared to the required value of 800€. The time limitation is reached when the time at which the design is finished is less then two months after the beginning date of the project. 22 april was the start of the project, so the prototype must be finished at the 22th of June to meet the time requirement.

4.4.2. BUOYANCY

At first it must be tested if the buoy is buoyant. To prevent damage on the electrical components on the buoy, the buoy must be launched on water, without electronics mounted on it. If no water flows inside the buoy, the buoy is buoyant. It is interesting to know how low the buoy floats in the water. This could be measured with a ruler.

4.4.3. MAXIMUM TILT AT STABLE POSITION

To test the requirement of the maximum tilt of 5° with respect to the horizon, the system must be started up in a stable situation. After calibration the lower part of the buoy must get a tilt in the roll direction. The system must control the platform to a stable situation. When the actuators do not move anymore the angle of the platform is measured with use of a plumb rule and a protractor. This measurement method is visualized in figure 4.13. To get useful data the angle of tilt of the lower part of the buoy must also be measured. This data must be coupled together in a table.

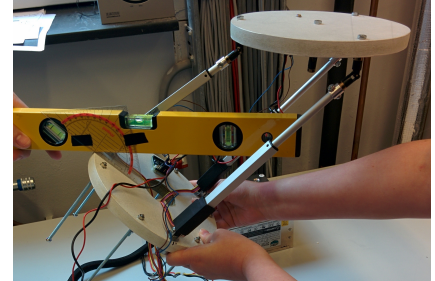


Figure 4.13: A picture of the measurement method

4.4.4. SPEED OF STABILIZATION SYSTEM

The hardest requirement in terms of testing is the measurement of the speed of the stabilization system. One method to measure the speed of the stabilization system is to make use of the second gyroscope. In that configuration the whole system is calibrated at first. Subsequently, the actuators are controlled such that the platform takes a predetermined angle. With the difference in angle between the upper and lower gyroscope could be verified if the desired configuration is reached. If this configuration is reached, the control system must be switched on. With a stopwatch the time of the movement of the actuators must be measured. The time must be stopped as soon as the tilt of the platform is less than 5° . That could not be determined very easily, so we wait until the moving of the actuators is stopped. We repeat these measurements, and take an average speed. This method must be repeated for different angles of tilt. This would result in a table with initial angles of tilt coupled with a reaction time. One of the big disadvantages of this test method is that the system has been adjusted by this test method. The testing system is part of the system. To avoid this problem we move the system manually. We give the lower part of the buoy a predetermined angle of tilt, and measure the time that the system needs to return at a stable position. One of the requirements is that the prototype must be a scaled model of the buoy, with a scaling factor of 5. The platform on the final buoy must be able to carry a weight of 55 kg (the weight of the ZephIR 300 module), so the platform on the prototype must be tested with a weight of 0.44 kg (this is a scaled weight in three directions). The effect of this weight on the speed of the stabilization system can be tested by comparing the measurements of the returning time with and without encumbering.

4.4.5. MAXIMUM COMPENSATION OF ANGLE OF TILT

To test the requirement of the maximum angle of tilt that the system could compensate, the platform must be moved until the actuators do not change their length anymore. With use of a plumb rule and a protractor this angle must be measured. Because the stabilization system is not completely orthogonal, this angle must be measured in multiple directions.

4.4.6. RELIABILITY

The system must be reliable. After one month the maximum angle of tilt after stabilization must be 5° . Because there is not enough time to test the prototype in this time scale, other test methods must be used. Deviation of the control system occurs after multiple movements of the system. The reliability of the system could therefore be tested with moving the system multiple times one after another. The maximum tilt at stable position is measured every time the system has been returned to its initial position. If there is a trend in this limited number of measurements, the system is not reliable.

4.4.7. LIMITATION OF THE ACTUATOR LENGTHS

The limitation of the lengths of the actuators could be tested by forcing the actuators down. With a multi-meter the output voltage of the potential feedback on the actuator could be measured. Also the length of the actuator could be measured, compared with the total length. Because damage on the actuators must be

avoided, the lengths are compared with the lengths that are specified in the datasheet. The same procedure could be followed for the maximum length of the actuator.

4.4.8. TOTAL SYSTEM

A final test must check if all components work well together. That implies that all components must be equipped at the buoy. The buoy must be launched to the water, after the calibration of the system is done. Because the design of a power supply fell out of the scope of the project, this would be a relatively risky test. It must be assured that the electrical components could not get in contact with water. Maybe this test could be done in a water tank with a movable bridge above it. The power supply must be mounted on the bridge, such that short circuits in the power supply are excluded. With motors waves with a predetermined frequency could be generated, and the angle of the upper platform could be measured with a laser mounted on the platform. The laser must point to the roof of the building, and according to the deviation of the laser point the angular deviation could be calculated.

5

RESULTS

5.1. COST AND TIME LIMITATION

Table 5.1 displays all the costs of the system.

Gyroscopes	€52.58
Microcontrollers	€0
Propulsion & position control	€145.56
Actuators	€384.00
Electronics	€37.02
Wood, mounting material	€40.41
Total	€659.57

Table 5.1: The costs of the prototype

The prototype is finished on the 16th of June.

5.2. BUOYANCY

The buoy is launched on the water, and it does not have any leakage of water. 6 cm of the black ring is still above the water level.

5.3. MAXIMUM ANGLE OF TILT AT STABLE POSITION

Table 5.2 shows the angles of tilt for the upper and lower part of the buoy after stabilizing. The measurements are done in the roll direction two times, to find if there is a trend in the deviation. The control system behaves the same in all directions. That will be showed in sections 5.4 and 5.5. Therefore more data is not added to this table.

Lower angle	Upper roll #1	Upper roll #2
40°	3°	-1°
30°	2°	-2°
20°	1°	-4°
10°	0°	-4°

Table 5.2: The angles of tilt for the upper and lower part of the buoy after stabilizing. The measurements are done without calibration in between.

5.4. SPEED OF STABILIZATION SYSTEM

Table 5.3 shows the measurements of the time that is needed to come back from the predetermined angles of tilt in four directions. Because the methods of measurement are not very reliable, multiple measurements

have been done. Table 5.3 only shows the average values of these measurements. Figure 5.1 shows the effect from encumbering the platform with a weight of 0.44 kg. Both subfigures show the time that the system needs to return to the stable position from the deviation of the lower part of the buoy. Figure 5.1a shows the reaction time without encumbering with the weight, figure 5.1b shows the reaction time with encumbering with the weight of 0.44 kg. The figures show that the effect from the weight on the returning time is very small. Figure 5.2 shows the average returning time from each angle of tilt in four directions, namely roll, pitch and two combinations from these directions.

Lower angle	Pitch [s]	Roll [s]	Pitch + roll [s]	Pitch - roll [s]
40°	2.9	2.9	3.4	2.8
30°	2.4	2.8	2.7	2.2
20°	1.8	1.8	2.1	1.8
10°	1.0	1.2	1.1	1.2

Table 5.3: This table shows the measurements of the time that is needed to return to a stable position for predetermined angles of tilt in the roll direction.

5.5. MAXIMUM COMPENSATION OF ANGLE OF TILT

The maximum angles of tilt that could be compensated in multiple directions are showed in table 5.4.

Direction	Maximum angle
Roll	38°
Pitch	41°
Roll + pitch	41°
-Roll + pitch	41°

Table 5.4: This table shows the maximum angles that the platform is able to compensate.

5.6. RELIABILITY

Table 5.5 shows the number of times that the system has been moved from its maximum angle of tilt, relative to the horizon, to a stable position, along with the compensated angle of tilt relative to the horizon.

# times of moving	pitch angle	roll angle
5	5°	3°
10	11°	2°
15	18°	1°
20	20°	5°

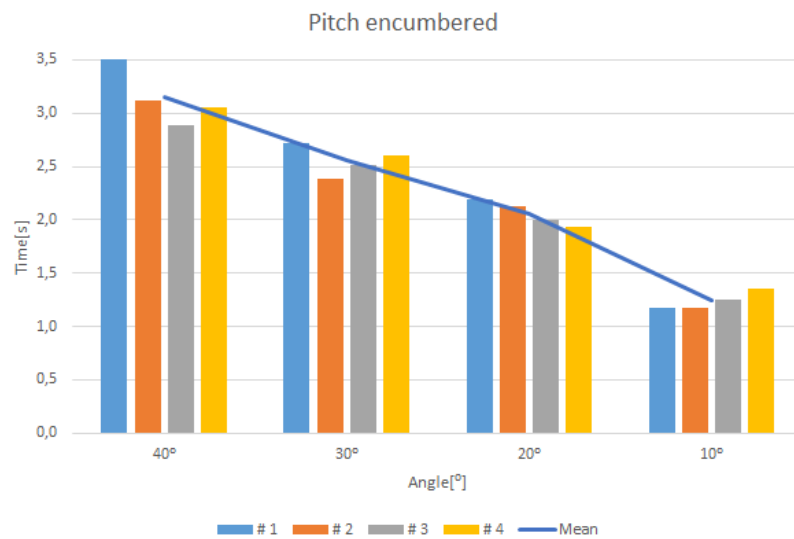
Table 5.5: The number of times the platform has been stabilized versus the angle of tilt in both directions after compensation

5.7. LIMITATION OF THE ACTUATOR LENGTHS

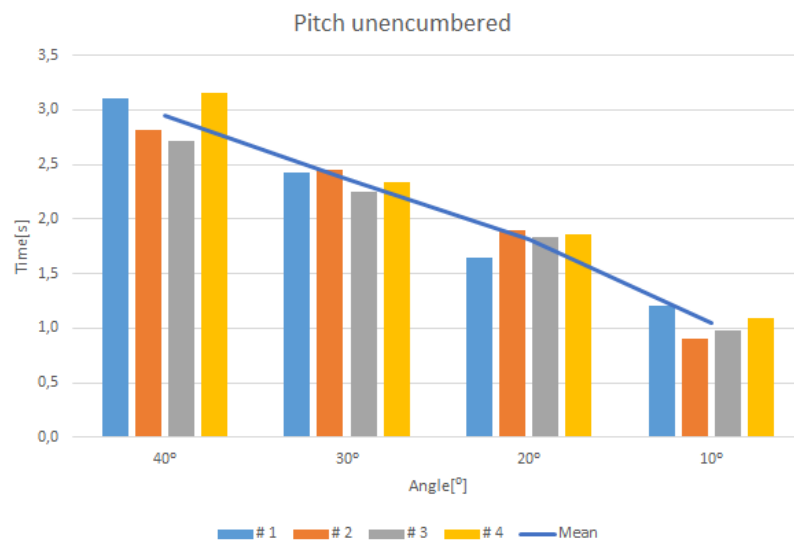
The outputs of the comparators that indicate if the actuators are outside their allowed range are directly connected to the LEDs on the microcontroller. If the actuators are outside their allowed range it can be seen that their length is slightly bigger or smaller than their smallest or biggest length. From the LEDs it can be read out that the comparators give the right output.

5.8. TOTAL SYSTEM

Due to limitations in time, room and safety, the control system has not been tested on the buoy on water.



(a) Pitch encumbered



(b) Pitch unencumbered

Figure 5.1: Effect of encumbering on the reaction time of compensation of angle of tilt in the pitch direction

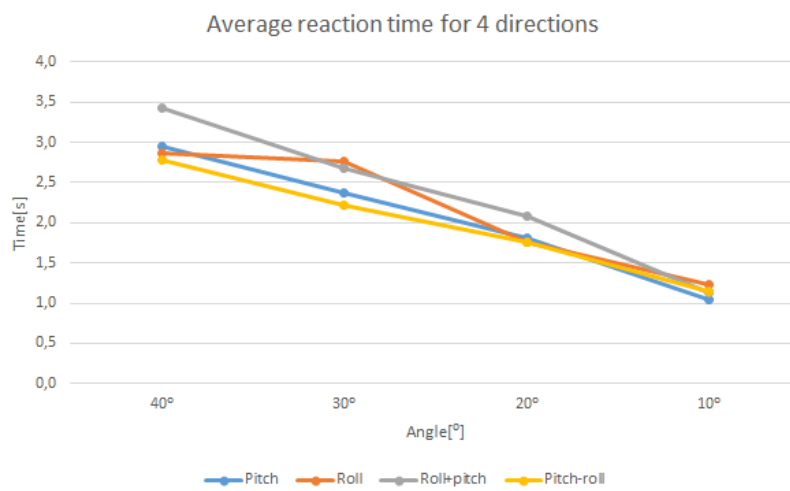


Figure 5.2: A plot of the average returning time for each direction and for each angle of tilt.

6

CONCLUSION

Section 5 describes the test results of the tests on the requirements. This section compares these test results with the requirements, and verifies if all requirements are met.

6.1. EVALUATION OF REQUIREMENTS

In this section is verified if all the requirements that are stated in section 2.2 have been met.

6.1.1. COST AND TIME LIMITATION

The total cost of the prototype is € 659.57, so the requirement that the prototype should not exceed costs of € 800 has been met. The prototype was finished on the 16th of June, so the prototype was built in time. So also the time requirement has been met.

6.1.2. BUOYANCY

The buoy is buoyant, with enough margins, so the requirement on the buoyancy has been met.

6.1.3. MAXIMUM TILT AT STABLE POSITION

As can be seen in table 5.2 the stabilization system controls the platform in that way that the platform has a maximum of 4° of tilt. The requirement that the stabilized platform should not have an angle bigger than 5° has been met. The platform needs frequently calibration, because noise on the measurements from the gyroscopes cause an extra tilt of the platform.

6.1.4. SPEED OF STABILIZATION SYSTEM

The requirement on the speed of the system has been expressed as follows: 'If the degree of tilt is greater than the maximum allowed degree of tilt of 5° the reaction time of getting back has to be smaller than 1 s, because the period of waves at the North Sea will be approximately 5 seconds.' This requirement is composed for two reasons. One reason is to assure that the system could resist impulses on the system. If the system somehow exceeds its limits, the time of getting back to a stable position must be small, to increase the availability of the measurement system. The other reason for the composition of this requirement is to ensure that the system is fast enough to stay within its limits on the angle of tilt. The results in table 5.3 show that the requirement on the speed of the stabilization system has not been met completely. Table 5.3 shows that the system needs 1.2 seconds to return to a stable position, if the lower part of the buoy has a deflection of 10°. The reaction time to return from the maximum angle is even 3 seconds. So if the system is affected with impulses that result in big deviations, the reaction time is too big. However, in our design we assumed 'normal' waves, with low frequencies (0.1-0.3 Hz). Also, section 4.2.1 has already shown that ripples on waves do not affect the angle of tilt much. That implies that if the platform gets small deviations from waves (< 5°) the requirement has been met nevertheless, because the system reacts within 1s for angles of deviation lower than 10°.

6.1.5. MAXIMUM COMPENSATION OF ANGLE OF TILT

As can be seen in table 5.4 the maximum compensation of tilt is at least 38°. That is bigger than 35°, so the requirement on the maximum angle of tilt has been met.

6.1.6. RELIABILITY

Table 5.5 shows that there is a trend in the measurements. The number of times the system has to stabilize, affects the angle of tilt at stable position. That means that the requirement on reliability has not been met, due to calibration errors of the gyroscope. Section 7.5 will describe some recommendations to achieve better results, and new solutions to meet also this requirement.

6.1.7. LIMITATION OF THE ACTUATOR LENGTHS

Section 5.7 describes that the actuators are kept inside their allowed region. The LEDs indicate that the comparison circuit works well. So the requirement on the limitation of the length of the actuators has been met.

7

DISCUSSION

This chapter makes several multiple recommendations to improve the behavior of the stabilizing control system.

7.1. IMPROVED MICROCONTROLLER

During the design of the prototype it became clear that it would be nice to have a microcontroller with more I/O ports, and with more AC/DC converters. The actuators are equipped with potential feedback. This feedback makes it possible to calibrate the actuators to certain lengths. At this moment calibration of the actuators is done by moving them down for long periods, and then raising them halfway. It is assumed that all actuators have the same speed. Observations on the actuators show that that is not the case. Due to this calibration method the platform has always been stabilized to an angle of tilt. The potential feedback from the actuators is an analogue signal. To make use of this signal in the microcontroller it has to be transformed to a digital signal with use of AC/DC converters. The currently used microcontroller has only one AC/DC converter equipped, and three of such converters are needed, for each actuator one. Additional I/O connections makes it also possible to control the actuators in an analogue way. At this moment the controlling of the actuators is digital: higher, lower or no change in the length of the actuators. Analogue controlling would make the movement of the platform more smooth.

7.2. IMPROVED ACTUATORS

The currently used actuators do not have enough speed, and are sensitive for damage. Due to cheap assembling, with for instance plastic casing, the actuators are very sensitive for torques due to motions in other directions than the direction at which the actuator could be adjusted. As a result of the choice for three actuators the actuators are experiencing torques due to the movement of the other actuators. To avoid damage to the actuators the actuators are mounted loosely on the platform. This result in deviations on the angle of tilt in stable position. A stronger and better assembled actuator would therefore result in a more stable system. The actuators that are used at this moment has a speed of 2 m/s , unencumbered. This speed limits the angular speed of the platform. Due to this limitation the reaction time requirement has not been met completely. If the speed of the actuators is increased, this reaction time could be reached nevertheless.

7.3. ONE ADDITIONAL ACTUATOR

Due to the choice for three actuators the actuators are experiencing a torque. Because the actuators are only made for linear movements this could cause damage on the actuators. An additional actuator could take away these torques. An extra actuator would also result in a faster system, because the weight of the platform is divided on more pillars. Also the control system could be made orthogonal: each angle of tilt could be compensated separately from each other. One additional actuator increases the costs of the platform. To avoid this extra cost, cheaper actuators could be used, because the weight each actuator has to carry is less.

7.4. IMPROVED H-BRIDGE

With digital controlling of the actuators the maximum speed of the actuators is assumed. However, at this moment the H-bridges decrease the voltage to the actuators, due to diodes inside the H-bridge. To increase the speed of the actuators this circuit should be modified, with for instance an operational amplifier to control the actuators with +12V and -12V.

7.5. SENSORS

7.5.1. KALMAN FILTER AND A COMBINATION OF SENSORS

The current setup only uses one gyroscope to obtain position information. Unfortunately, gyroscope output tends to drift on the long term, which produces uncorrectable noise in the position measurements. This can be compensated using a Kalman filter. This type of filter can combine multiple types of sensors and determine their amount of noise. In our case, a combination of an accelerometer (a device that measures angular acceleration) and a gyroscope (a device that measures angular velocity) can be used. An accelerometer does not suffer from long term inaccuracies, but is very noisy in the short term. For a gyroscope, this is the other way around. The Kalman filter can combine the advantages of both types of sensors and produces a reduced-noise output of one of the sensors.

7.5.2. USING ONLY ONE SENSOR

At this moment two gyroscopes are mounted on the buoy, while only the one on the upper platform is used effectively. The lower gyroscope could have been used for testing, but in the final design this sensor could be omitted, to decrease the costs of the prototype.

7.6. IMPROVED LENGTH LIMITATION CIRCUIT

The comparators used in the current design have a floating output pin. The output is connected with a pull-up resistor. To decrease the power consumption and to increase the speed of the comparator circuit another comparator could be used, of which the output is connected with a transistor to the supply voltage.

7.7. IMPROVED SIMULATION AND DERIVATION OF TRANSFER FUNCTION

Due to time restrictions there was not much time for simulation of the control system. Further simulation could be helpful to investigate the behavior of a buoy on the North Sea. A derivation of the transfer function of the platform could be used for analogue controlling of the actuators. This would make the system faster, and more reliable.

7.8. FEEDFORWARD CONTROL SYSTEM

It has been already mentioned earlier, but it is assumed that waves have a stochastic behavior. This makes it attractive to design a feed forward system, because the next state of the waves could be predicted. The state of the system could be adjusted such that the angle should stay zero. In such a system two sensors are needed. One mounted on the lower part of the buoy that measures the state of the buoy, and one on the upper part of the platform, to slightly improve the angle of tilt. The lower sensor is the most important one in such a system. This sensor determines the angle of the buoy. From this data the next state of the buoy could be deduced. This makes it possible to react before the deviation has been caused. In theory this would make the deviation of the angle of tilt lower.

7.9. CONCLUDING REMARKS

With the implementation of these recommendations one may expect that the stabilization system would behave faster, smoother and more reliable. It has to be kept in mind that more precision, speed and reliability would result in higher costs than required in section 2.

BIBLIOGRAPHY

- [1] Donella H. Meadows, Dennis L. Meadows, Jorgen Randers, William W. Behrens III, *The limits to Growth* (Universe Books, 1972).
- [2] Lou van der Sluis, *Electrical Power System Essentials* (Wiley, 2009) p. 45.
- [3] Madsen and Krogsgaard, *Offshore Wind Power 2010*, BTM Consult (2010).
- [4] Niki Nixon, *Timeline: The history of wind power*, <http://www.theguardian.com/environment/2008/oct/17/wind-power-renewable-energy> (2008).
- [5] European Wind Energy Association, *Oceans of Opportunity*, http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/Offshore_Report_2009.pdf (2009).
- [6] Hamid Alemi Ardakani, Thomas J. Bridges, *Shallow-water sloshing in vessels undergoing prescribed rigid-body motion in three dimensions*, <http://personal.maths.surrey.ac.uk/st/T.Bridges/SLOSH/AAB-Part2-Colour.pdf> (2014).
- [7] Madaxa, *Business plan presentation*, Presentation (2014).
- [8] Oceanor, *SEAWATCH Wind LiDAR Buoy*, http://www.oceanor.com/related/Datasheets-pdf/SEAWATCH_Wind_LiDAR_Buoy.pdf (2012).
- [9] Mathieu Baas, Annemieke Pannekoek, *Bachelor of Science Thesis - The Platform and Overall Design of an Actively Stabilised, Manoeuvrable Buoy for Offshore Wind Assessment*, (2014).
- [10] Tom Hogervorst and Arjan van der Kruijt, *Bachelor Thesis - Manoeuvrable Buoy for Offshore Wind Assessment*, (2014).
- [11] Health and safety executive(HSE), *Wind and wave frequency distributions for sites around the British Isles*, <http://www.hse.gov.uk/research/otopdf/2001/oto01030.pdf> (2001).
- [12] ZephIR Lidar, *ZephIR 300*, <http://www.zephirlidar.com/products/zephir-300> (2014).
- [13] Parallax, *Gyroscope Module 3-Axis L3G4200D*, <http://www.parallax.com/sites/default/files/downloads/27911-Gyroscope-3-Axis-L3G4200D-Guide-v1.1.pdf> (2013).
- [14] Firgelli, *Miniature Linear Motion Series - L16*, http://www.firgelli.com/pdf/L16_datasheet.pdf (2010).
- [15] Oceanor, *Fugro launches Seawatch Wind Lidar Buoy at global offshore wind*, http://www.oceanor.com/newsroom/News_overview_2012/Lidar (2012).
- [16] Offshorewind.biz, *Dong, FLiDAR Kick Off Floating Offshore Wind Measurement Campaign in Irish Sea*, <http://static.offshorewind.biz/wp-content/uploads/2013/06/Dong-FLiDAR-Kick-Off-Floating-Offshore-Wind-Measurement-Campaign-in-Irish-Sea.jpg> (2013).
- [17] OWA, *About OWA*, <http://www.deme-group.com/owa/about-owa> (2014).
- [18] 3E, *About 3E*, <http://www.3e.eu/about-3e/> (2014).
- [19] Flidar, *Cost-effective, Accurate Offshore Wind Measurements*, http://www.flidar.com/wp-content/uploads/2013/11/FLiDAR_Intro_201311.pdf (2013).
- [20] KIC InnoEnergy, *Neptune project tests its buoy at sea*, <http://www.kic-innoenergy.com/blog/2013/05/30/neptune-project-tests-its-buoy-at-sea/> (2013).

- [21] KIC Innoenergy, *Neptune - A solution to the current challenges of wind measuring for offshore wind farms*, http://www.kic-innoenergy.com/iberia/wp-content/themes/colocations_new/kic/neptune/neptune.pdf (2013).
- [22] Neptune, *Challenges for such a lidar buoy*, <http://neptool.eu/challenges-for-such-a-lidar-buoy/> (2014).
- [23] Neptune, *Steps of development*, <http://neptool.eu/steps-of-development/> (2014).
- [24] Offshorewind.biz, *VIDEO: AXYS WindSentinel™ Deployment*, <http://www.offshorewind.biz/2013/02/07/video-axys-windsentinel-deployment/> (2013).
- [25] Graham Howe, *Developing a Buoy-Based Offshore Wind Resource Assessment System*, <http://axystechnologies.com/wp-content/uploads/2014/03/Developing-a-Buoy-Based-Offshore-Wind-Resource-Assessment-System.pdf> (2014).
- [26] Axy's Technologies, *WindSentinel datasheet*, <http://axystechnologies.com/wp-content/uploads/2013/11/WindSentinel-digital-Data-Sheet.pdf> (2013).
- [27] Michael K. Masten, *Inertially Stabilized Platforms for Optical Imaging Systems*, <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4430219> (2008).
- [28] S. W. M. John D. Adams, *Gyroscopic roll stabilizer for boats*, (2003).
- [29] D. Stewart, *A platform with six degrees of freedom*, Proceedings of the Institution of Mechanical Engineers (1965).
- [30] Eric Monmasson and Lahoucine Idkhajine and Mohamed Wissem Naouar, *FPGA-based microcontrollers*, <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5742590> (2011).
- [31] Florida Center for Instructional Technology, *Waves in the Ocean*, <http://fcit.usf.edu/florida/teacher/science/mod2/resources/waves.pdf> (2005).
- [32] Bjarne Stroustrup, *The C++ programming language* (Addison-Wesley, 2013).
- [33] AVR GCC, *AVR Libc Home Page*, <http://www.nongnu.org/avr-libc/> (2011).
- [34] Nathan Hufstetler, *Implementing a PID Control System on a Microcontroller*, <http://wanovak.com/ece480/docs/appnote/hufstetler.pdf> (2013).
- [35] Tim Wescott, *PID without a PhD*, <http://igor.chudov.com/manuals/Servo-Tuning/PID-without-a-PhD.pdf> (2000).
- [36] Thor I. Fossen, *Guidance and Control of Ocean Vehicles* (John Wiley and Sons, 1999) pp. 6–30.
- [37] James F. Wilson, *Dynamics of offshore Structures* (John Wiley and Sons, 2003).
- [38] MATLAB, *Estimate state-space model using a subspace method. - MATLAB n4sid - MathWorks Benelux*, <http://www.mathworks.nl/help/ident/ref/n4sid.html> (2014).
- [39] Larimore, W.E., *Canonical variate analysis in identification, filtering and adaptive control*, Proceedings of the 29th IEEE Conference on Decision and Control.
- [40] Verhaegen, M., *Identification of the deterministic part of MIMO state space models*, Automatica **30**.
- [41] Jansson, M., *Subspace identification and ARX modeling*, 13th IFAC Symposium on System Identification (2003).
- [42] User:Pbroks13 on Wikipedia, *File:Buoyancy.svg*, <http://commons.wikimedia.org/wiki/File:Buoyancy.svg> (2008).
- [43] Paul A. Tipler and Gene Mosca, *Buoyancy and Archimedes' Principle*, in *Physics for scientists and engineers* (Susan Finnemore Brennan, 2008) 6th ed., pp. 432–438.

- [44] C. Beels, J.C.C. Henriques, J. De Rouck, M.T. Pontes, G. De Backer and H. Verhaeghe, *Wave energy resource in the North Sea*, <http://repositorio.lneg.pt/bitstream/10400.9/404/1/1004.pdf> (2007).
- [45] Jean-Marc Irazabal and Steve Blozis, *AN10216-01 $\dot{P}C$ Manual*, http://www.nxp.com/documents/application_note/AN10216.pdf (2003).
- [46] Texas Instruments, *LM139, LM139A, LM239, LM239A, LM339, LM339A, LM2901, LM2901V Quad differential comparators*, <http://datasheet.octopart.com/LM339N-Texas-Instruments-datasheet-7280603.pdf> (2006).
- [47] Atmel, *Atmel8 datasheet*, http://www.atmel.com/Images/Atmel-2486-8-bit-AVR-microcontroller-ATmega8_L_datasheet.pdf (2013).
- [48] Olimex, *LPC-P1343 development board user's manual*, <https://www.olimex.com/Products/ARM/NXP/LPC-P1343/resources/LPC-P1343.pdf> (2013).