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# Development of Software Tool for Identification of Ballast Errors in Autonomous Underwater Vehicles

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Master of Science in Cybernetics and Robotics
Submission date: June 2014
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**Fakultet for informasjonsteknologi, matematikk og elektroteknikk**
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# HOVEDOPPGAVE

| | |
|---|---|
| Kandidatens navn: | Nina Fjelldalen Lillemoen |
| Fag: | Teknisk kybernetikk |
| Oppgavens tittel (norsk): | Utvikling av software-verktøy for identifikasjon av ballastfeil i autonome undervannsfarkoster |
| Oppgavens tittel (engelsk): | Development of Software Tool for Identification of Ballast Errors in Autonomous Underwater Vehicles |

**Background**
Autonomous underwater vehicles (AUVs) are usually designed to be neutrally buoyant in water by adjusting ballasting weights. Ballasting is also important to get the correct trim angles for the vehicle. However, changes in salinity for different operating areas change the required ballasting. In addition, vehicles with modular payload sections can change weight between runs and the ballasting must be re-done. Today, the ballasting process is manual and requires skill and experience.

**Tasks**

1. Design and develop of a system for automatic identification of required vehicle ballasting in an autonomous underwater vehicle.
2. Make a test routine to test the system for different conditions. Kongsberg Maritime can provide data from real vehicle missions.

**Oppgaven gitt:** Besvarelsen leveres: 06.01.2014
Besvarelsen levert: 02.06.2014

**Veiledere:** Professor Kristin Y. Pettersen, NTNU
Principal R&D Engineer Even Børhaug, Kongsberg Maritime

Trondheim, den 15.05.2014

Kristin Y. Pettersen
Faglærer

# Preface

This Master Thesis was written at the Department of Engineering Cybernetics at the Norwegian University of Science and Technology in Trondheim, Norway, during the spring semester of 2014. The Master Thesis concerns the design, development and implementation of a system for identification of ballast errors in autonomous underwater vehicles.

The Master Thesis was commissioned by Kongsberg Maritime for one of their autonomous underwater vehicles called HUGIN 1000. Kongsberg Maritime contributed with a supervisor for the project, specifications for the autonomous underwater vehicle and mission data.

Kongsberg Maritime's HUGIN 1000 has no system for identification of ballast error. Today, all ballasting of the HUGIN 1000 is done manually, which is time-consuming and requires experienced human operators. Kongsberg Maritime, therefore, wanted to automate the ballasting process and this is the motivation for this Master Thesis.

Trondheim, June 1st 2014

Nina Fjelldalen Lillemoen

Nina Fjelldalen Lillemoen

# Acknowledgement

I want to thank my supervisor at the department of Engineering Cybernetics, Professor Kristin Y. Pettersen, for all guidance and support. I, also, want to thank Even Børhaug at Kongsberg Maritime for all the help and for answering all my questions. Thanks to Kongsberg Maritime for allowing me to use real mission data and providing specifications of their HUGIN 1000.

I would like to thank my classmates and my office partners Hans Erik Frøyen and Simen Andersen for being available for discussions. Thanks also go to my parents, Bente Fjelldalen Lillemoen and Jon Lillemoen, for moral support and encouragement, and for brainstorming weighing methods with me for hours. Finally, I want to thank my good friend Siri Holte Mathisen for proofreading this Master Thesis.

-Nina F.L.

# Abstract

An autonomous underwater vehicle (AUV) with correct ballast will be energy efficient and will easily follow its programmed mission path. A ballast error may result in increased power consumption. It can also prevent an AUV from following its mission path and in severe cases a ballast error can cause an AUV to crash. The correct ballasting is achieved by carefully adjusting the ballast of the AUV so that it gains a stable state of equilibrium with neutral buoyancy. The state of equilibrium and buoyancy are affected by changes in the AUV's weight due to its payloads and variations in the water salinity. The ballasting, therefore, has to be checked and possibly re-done between missions to correct any ballast errors.

Kongsberg Maritime has an AUV called HUGIN 1000. Today, the ballasting process of HUGIN 1000 is done manually, which is time-consuming and requires experience. For this reason, Kongsberg Maritime commissioned this Master Thesis, with the objective of developing a software tool that will automate the ballasting process by identifying ballast errors and determine suitable ballast adjustments.

The software tool will form a static ballast system for AUVs, which will identify necessary adjustments in ballast based on different vehicle measurements and mission data. The system includes three modes of operation that have been developed to perform different tasks and handle the varying access to mission data. These modes include a first, pre and post mission mode. The first mission mode is used before the very first mission when no mission data is available. It will calculate a suitable ballast adjustment based on manual measurements. The pre mission mode will calculate an improved ballast adjustment based on collected mission data, which has been collected by the AUV during a mission. It is the task of the post mission mode to process the data and then identify any ballast errors based on the data.

The result of the Master Thesis is a software tool that has been designed and implemented including the results of tests performed on it. Based on the results and a literature survey, possible improvements are suggested and discussed. These improvements include additions and extensions to the implemented system and a new active ballasting system. Finally, the conclusion is that a system for identification and adjustments of ballast errors in AUVs, which has been developed and implemented, can be justified by the AUVs' requirement for correct ballast. Moreover, it would be beneficial as it will make the process of ballasting quicker and easier.

# Sammendrag

En autonom undervannsfarkost (AUV) med korrekt ballast vil være energieffektiv og kan enkelt følge en forhåndsprogrammert operasjonsvei. En ballasteringsfeil kan medføre økt energi forbruk. En AUV med ballastfeil kan også bli hindret fra å følge operasjonsveien sin og i alvorlige tilfeller kan ballastfeil forårsake ulykker. Korrekt ballast kan oppnås ved nøyaktig justering av AUV-ens ballast slik at den er i stabil likevekt med nøytral oppdrift. Likevektstilstanden og flyteevnen påvirkes av endringer i AUV-ens vekt som følge av nyttelasten og variasjoner i vannets saltholdighet. Ballasten må derfor sjekkes og muligens justeres mellom oppdrag for å korrigere eventuelle ballastfeil og sørge for stabil likevekt med nøytral oppdrift.

Kongsberg Maritime har en AUV kalt HUGIN 1000. I dag må ballastprosessen utføres manuelt på HUGIN 1000, noe som er tidkrevende og krever erfaring. Kongsberg Maritime bestilte derfor denne hovedoppgaven. Formålet med hovedoppgaven er å utvikle et software-verktøy som kan automatisere ballastprosessen ved å identifisere eventuelle ballastfeil og finne en passende ballastjustering.

Software-verktøyet utgjør et statisk ballastsystem for AUV-er som skal være i stand til å identifisere nødvendige ballastjuseringer basert på ulike farkost-måleringer og operasjonsdata. Systemet har tre operasjonsmoduser som er utviklet for å utføre ulike oppgaver og håndtere varierende tilgang på operasjonsdata. Disse modusene inkluderer en første-, før- og etter-operasjonsmodus. Første-operasjonsmodusen brukes før det aller første oppdraget når ingen operasjonsdata er tilgjengelige, derfor vil en passende ballastjustering baseres på manuelle måleringer. Før-operasjonsmodusen beregner en forbedret ballastjustering på bakgrunn av operasjonsdata som har blitt samlet av AUV-en i løpet av et oppdrag. Det er oppgaven til etter-operasjonsmodusen å behandle operasjonsdataene og identifisere eventuelle ballastfeil basert på datene.

Resultatet av hovedoppgaven vil være software-verktøyet som ble designet og implementert, inkludert resultatene av systemtestene som er gjort. På bakgrunn av disse resultatene og et litteraturstudium blir mulige forbedringer foreslått og diskutert, disse forbedringene omfatter tilføyelser og utvidelser av det implementerte systemet og et nytt aktivt ballasteringssystem. Til slutt kan det konkluderes med at et system for identifikasjon og justeringer av ballastfeil i AUV-er, som har blitt utviklet og implementert, kan bli rettferdiggjort av AUV-enes behov for riktig ballast. Videre vil det være fordelaktig ettersom det vil gjøre prosessen med ballastering raskere og enklere.

# List of Abbreviations

Abbreviations that will be used in this paper:

- **AUV** - **A**utonomous **U**nderwater **V**ehicle
- **CB** - **C**enter of **B**uoyancy
- **CG** - **C**enter of **G**ravity
- **CO** - **C**enter of **O**bject
- **DOF** - **D**egrees **O**f **F**reedom
- **ROV** - **R**emotely **O**perated **V**ehicles

Explanation of terms used in this paper:

- **Adjustment weights** - the weights available to use for ballast adjustments
- **Autonomous underwater vehicle** - an autonomous unmanned submarine vehicle
- **Ballast** - the substance of a vehicle, which can be adjusted
- **Ballast error** - incorrect ballast, which makes vehicles too heavy, too light, tilt or unstable
- **Mission** - an operation/journey made by a vehicle to do a task
- **Mission mode** - system modes that solve different tasks, which are used before and after missions
- **Orientation** - the pitch and roll angles of an object
- **Points of adjustment** - locations on the AUV where weights can be added to adjust the ballast
- **System** - the software tool that will be designed and implemented
- **Weight/buoyancy balance** - the relationship between the weight of the vehicle and the buoyancy force acting on it

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# Part I

# BACKGROUND AND THEORY

# Chapter 1

# Introduction

This Master Thesis concerns the design and development of a software tool for identification of ballast errors in autonomous underwater vehicles (AUVs). Kongsberg Maritime commissioned it for one of their AUVs called HUGIN 1000. The thesis work was carried out during the spring semester of 2014 at the Department of Engineering Cybernetics at the Norwegian University of Science and Technology.

This introduction presents the background and motivation for the Master Thesis, and then objective and purpose will be stated with the limitations that are present. Finally, the approach used is explained and an overview of the structure of this report is given.

## 1.1 Background and motivation

There are two major types of modern underwater vehicles; manned and unmanned. According to [14], unmanned vehicles are partially or fully robotic machines and include remotely operated vehicles (ROVs), autonomous underwater vehicles and hybrid underwater vehicles. The ROVs have a cable that transmits electrical power, data, navigational information and sensor reading from a boat [14]. A human operator on a boat will control the ROV through its cable in real-time. In contrast to ROVs, the AUVs have no cable, which make them free-swimming [14]. Without the cable, the AUVs have to be pre-programmed to operate without a human operator. They also have to carry their entire energy requirement with them since they have no external power supply.

The Norwegian company Kongsberg Maritime produces several different AUVs, amongst them are the HUGIN 1000 (see Figure 1.1). HUGIN 1000, like AUVs in general, is designed to be neutrally buoyant in a stable state of equilibrium in water so that it will neither float up or sink, pitch or roll, if no thrust is applied or the rudders are used [14]. However, AUVs are not by default in a stable state of equilibrium. They experience ballast errors if their ballast is not correctly configured, which will affect their behavior and performance during missions. A ballast error will occur if the AUV's weight and the buoyancy force acting on it do not counteract each other, which results in a weight/buoyancy imbalance. A ballast error will also occur if the weight distribution does not place the center of gravity (CG) right below the center of buoyancy (CB), which will cause a pitch or roll angle error.

The weight and the CG of an AUV will be affected by the configuration of its payloads. AUVs normally have several payloads with different sensors and processing devices to enable them to perform different types of operational tasks. All these payloads may have different weight and can be mounted at different locations inside the AUV. The configuration of the payloads will therefore affect the weight and the CG of the AUV, which can cause weight/buoyancy imbalance and pitch and roll errors. A weight/buoyancy imbalance can also be caused by changes in the buoyancy force acting on the AUV. The buoyancy force depends on the salinity and temperature of the water, which varies with the operational depth and can vary in different waters. The buoyancy force might therefore change between missions, and cause a weight/buoyancy imbalance. The ballasting must therefore be carefully adjusted before each mission to gain a stable state of equilibrium with neutrally buoyant, and consequently make the AUV energy efficient and able to easily follow its pre-programmed mission path. Today, AUVS are increasingly used in inaccessible areas and in environments that can be dangerous for humans. It is therefore important that the AUVs are functioning properly, that they able to follow their predefined tasks and that they are energy efficient, so that humans do not have to be in these areas to aid or pick up the AUVs.

Today, Kongsberg Maritime has no existing automatic system for identification of ballast errors. The ballasting process is done manually by adding additional weights to the AUV. This process requires skills and experience, and it is a time-consuming process, which means that AUV must spend some time in the docking for ballasting process. Kongsberg Maritime's customers, however, are very interested in having the HUGIN 1000 operating underwater as much as possible. Kongsberg Maritime, therefore, wants to automate this ballasting process so that their customers do not have to spend so much time manually ballasting the vehicle. The objective of this Master Thesis will therefore be to develop a software tool for automatic identification of ballast errors. This system should both identify and determine suitable ballast adjustments to make the AUV neutrally buoyant in a stable state of equilibrium.

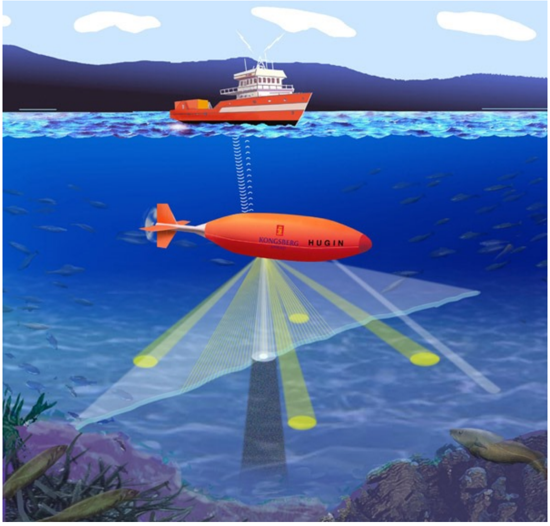

Figure 1.1: Kongsberg Maritime's HUGIN 1000 on mission[1]

## 1.2 Objective and purpose

The objective and purpose of this Master Thesis is to design, development and implement a software tool for identification and adjustment of ballast errors. The system will be designed to meet Kongsberg Maritime needs and requirements, and the system will be restricted by the limitations that concern their AUV, HUGIN 1000. The system will replace the manual process of ballasting the AUV that is used by Kongsberg Maritime today. To be able to perform all its tasks, the system will have different modes of operation that identify ballast errors and determine suitable ballast adjustments.

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[1] The figure is the courtesy of Kongsberg Maritime at `http://www.gulfofmaine-census.org/education/research-technology/platforms/`

The ballast adjustments should produce a stable state of equilibrium with neutral buoyancy. Ballast errors will be identified by using the mission data collected by the AUV during missions. Any changes in salinity, temperature and depth should be considered. The system should map the required ballast adjustments for a human operator that has to perform the actual adjustment by adding or removing weights on the AUV. The system should therefore aim to be easy to learn, use and operate so that it will be preferred over the manual process and make the ballasting process faster.

### 1.2.1 Limitations

The system developed in this Master Thesis is object for several limitations. The system is limited by the specifications given by Kongsberg Maritime; they want a static ballast system with different modes of operation that identify ballast errors and map suitable adjustments for a human operator.

The ballast of the HUGIN 1000 can only be adjusted by adding or removing weights on the AUV, which will only enable adjustment of the weight and the CG. According to the specifications given by Kongsberg Maritime, the buoyancy and the CB are fixed and cannot be changed. The CG can be moved by adding different weights to the AUV, however, on the HUGIN 1000 weights can only be added on four given point of adjustment, which reduces the number of possible weight distributions. In addition, only a small number of different weights are available for adding or removing.

At this stage, the only AUV that can be selected in the system is the HUGIN 1000. However, the system is modular and general, it can easily be expanded to provide identification of errors and adjustments for other AUVs too.

## 1.3 Approach

The work on this Master thesis started right after the beginning of the autumn semester, 2013. During the autumn semester preliminary work for the Master Thesis was done. The actual work on the Master Thesis started January $6^{th}$ of 2014 with meetings with the supervisors, Professor Kristin Y. Pettersen and Even Børhaug. During these meetings the purpose, objective and scope of the Master Thesis was deduced.

The first step was to derive and set up system specifications according to the description of the Master Thesis and Kongsberg Maritime's requirements (see Section 5.1), and based on these was the system designed (see Chapters 4 and 5). After designing the system it was implemented using Matlab (see Section 4.1). When implementation was finished, the system was tested according test routines (see Chapter 6). The results were analyzed (see Chapter 7). Then possibilities for improving the system were researched (see Chapter 8). A small literature survey was carried out to research improvements.

## 1.4 Structure

This Master Thesis is five parted and consists of ten chapters, a Bibliography and appendices. The structure of the paper is organized in chapters as follows; Part 1 provides the background and theory that form the basis of this Master Thesis. Chapter 1 is the introduction where the context of Master Thesis is presented and the purpose is explained along with the limitations. The theory that are utilized in developing the system is presented in Chapter 2. Chapter 3 presents Kongsberg Maritime's HUGIN 1000.

Part 2 presents the system and the design and implementation of it. Chapter 4 lists the design issues and decisions that were encountered during the work with this Master Thesis. Chapter 5 presents the system that was designed, developed and implemented, the system specifications are listed and the following subsections are devoted to give an overview of the mission modes and the different system features, and explains how ballast errors are detected and how the required ballast adjustments are determined.

In Part 3 will the system testing be explained, it further contains the results of the tests with discussions and possible improvements. The test routines used to test the system are described in Chapter 6. The results of the system testing are presented in the Chapter 7 along with discussions of the results. Chapter 8 is devoted to improvements and extensions for the system, which includes how to make the system more accurate, more general and fully-automatic.

Part 4 contains concluding remarks and further work. The concluding remarks are presented in Chapter 9, where the objective of the thesis will be reassessed in context of the results. Chapter 10 encloses possible further work. Finally, the Bibliography is presented with all the references that have been used. At the end, in Part 5, the appendices with additional material are attached.

# Chapter 2

# Theory

In this chapter, the theory relevant to this Master Thesis will be presented. Some of the theory is used directly to derive computations for the system, while other parts of the theory are used to explain design decisions and different accepts of the system and the AUVs that are discussed. In addition, a definition of ballast errors are given.

## 2.1 Reference frame and six degrees of freedom

The most commonly used coordinate frame systems for marine control systems are the Earth-centered inertial (ECI), Earth-centered Earth-fixed (ECEF), North-East-Down (NED) and BODY. The ECI and ECEF frames are variances of earth centered coordinates systems. The ECI frame is an inertial frame that do not rotated with the Earth, while ECEF rotate with the Earth. The NED system is a geographic coordinate system defined relative to the Earth. The BODY system is a vehicle coordinate system that is moving and rotating with the vehicle, according to [11].

An AUV can move in six degrees of freedom (DOFs), which determines its position and orientation within the chosen coordinate frame (see Figure 2.1). The general motion of a marine vehicle in the BODY frame can be, according to [11], described by the 6 DOFs as:

$$\eta = \begin{bmatrix} x & y & z & \phi & \theta & \psi \end{bmatrix}^T \tag{2.1}$$

The first three coordinates are the positions along the axes, $x$, $y$ and $z$, and their corresponding translational motion, $u$, $v$ and $w$. The last three coordinates are the orientations, $\phi$, $\theta$ and $\psi$, and their corresponding rotational motion, $q$, $p$ and $r$.

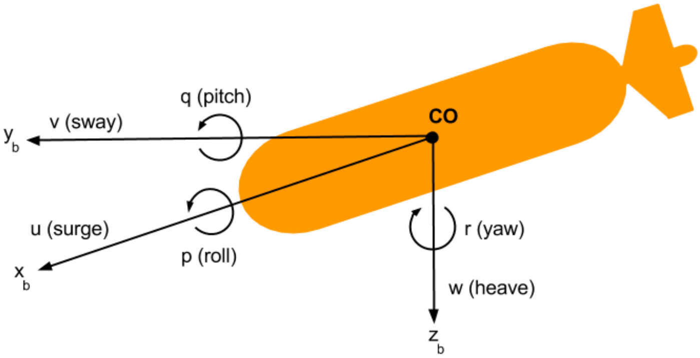

Figure 2.1: The 6 DOFs in the BODY frame

The orientations, $\phi$, $\theta$ and $\psi$, are defined accordingly:

- The pitch, $\phi$, is positive when the nose tilts upwards (see Figure 2.2), so when diving, the pitch will be negative, while it will be positive when surfacing
- The roll, $\theta$, is positive when the port side tilts upwards (see Figure 2.3)
- The yaw, $\psi$, is positive when the AUV turns with the clock

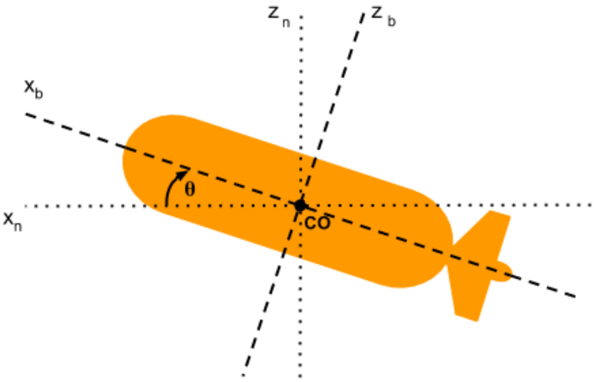

Figure 2.2: The pitch angle when the AUV is seen from its port side

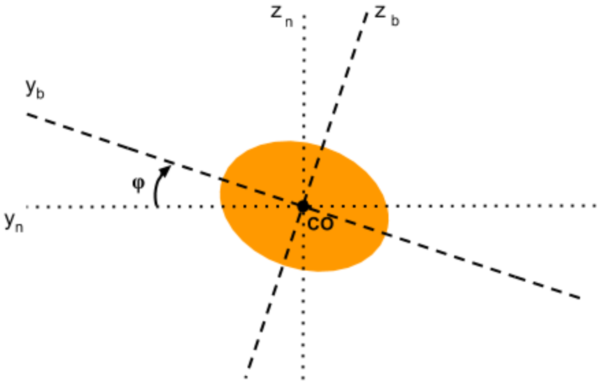

Figure 2.3: The roll angle when the AUV is seen from behind

## 2.2 Water properties

The water properties that are relevant when considering the ballasting of an underwater vehicle are pressure, salinity, density and temperature, which are all affected by the water depth.

### 2.2.1 Water pressure

The water pressure can be derived from the expression for pressure, $p$, which is the force, $F$, exerted on an area, $A$:

$$p = \frac{F}{A} \tag{2.2}$$

The force, $F$, is according to Newton's 2nd law $F = ma$. The $a$ is the acceleration that in this case is the gravitational acceleration, $g$. The mass of the water, $m$, is given by $m = V\rho$, where $\rho$ is the water density. The volume is a product of the area and the water depth, hence $V = Ah$. The water pressure can therefore be expressed by:

$$p = \frac{mg}{A} = \frac{V\rho g}{A} = \frac{hA\rho g}{A} = \rho g h \tag{2.3}$$

By viewing Equation 2.3, it can be seen that the pressure increases with depth and water density.

### 2.2.2 Salinity

Salinity expresses the concentration of salt in water [14]. Usually, the salinity is given as parts of salt per thousand of the water mass, which gives the unit parts per thousand (ppt).

The salinity depends on several different local conditions like evaporation, rain, river inflow and soil. It will be significantly different in sea water, brackish and freshwater (see Table 2.1, courtesy of [5]).

| Water type | Salinity level |
|---|---|
| fresh water | about 0.5 ppt |
| brackish water, mildly | 1 - 5 ppt |
| brackish water, moderately | 5 - 15 ppt |
| brackish water, heavily | 15 - 30 ppt |
| sea water | 30 - 50 ppt |

Table 2.1: The salinity in different water types

### 2.2.3 Water density

Density expresses the ratio between mass and volume:

$$density = \frac{mass}{volume} \tag{2.4}$$

For the calculations done in this Master Thesis, a more complex and accurate computation of water density is applied, which will be presented in Section 4.5.

The water density is a factor in the buoyancy force, while the water density is affected by the temperature and salinity of the water and pressure at the operating depth. The water density decreases as the temperature increases and as the salinity level decreases.

### 2.2.4 Temperature

When the water is not frozen, the water temperature tends to be warmer near the surface than in deeper water [14]. This is because the sun warms up the water near the surface and the warm water floats on top of the cold water because warmer water is less dense than cold water. However, as said in [14], wind and waves will stir up the water and mix the warmer water and colder water. The warm and cold layers of water are separated by a thermocline where the temperature changes dramatically. Under this line the temperature of the water will decease further. Below 1 000 meters the ocean is about 4 °Celsius, which is when water is at its densest [14].

## 2.3 The buoyancy force and the CB

An underwater vehicle will experience buoyancy in water, which is one of the restoring forces [11]. Buoyancy, B, is an upwards force exerted by a fluid on an object immersed in it. The buoyancy acts from the CB of the immersed object. Buoyancy is defined as:

$$B = \rho g \nabla \tag{2.5}$$

Where $g$ is the acceleration of gravity (positively downwards), $\rho$ is the water density and $\nabla$ is the volume of the displaced fluid. $g$ and volume of the vehicle are assumed fixed, only the density of the water can change the buoyancy force. The water density can be calculated based on known data collected during previous missions. This implies that the buoyancy force and then the CB can be calculated. According to [12], by assuming that the water has constant density, the CB is the geometric centroid of the displacement volume, $\nabla$:

$$CB = [x_B, y_B, z_B] = \frac{1}{\nabla} \int (x, y, z) d\nabla \tag{2.6}$$

## 2.4 The gravitational force and the CG

The other restoring force acting on an underwater vehicle is the gravitational force. This force acts downwards from the CG and is a product of the vehicle's weight. The weight of a submerged vessel is defined as:

$$W = mg \tag{2.7}$$

Where $g$ is the acceleration of gravity (positively downwards) and $m$ is the mass of the vehicle. Here too, the $g$ is assumed fixed, therefore only the mass of the vehicle can change the weight.

The distribution of weight in the vehicle will affect its CG, which is the mean position of the mass in a body. The CG can be calculated with some inaccuracy as a system of $n$ particles, $P_i$ for $i = 1, \ldots, n$, each with a mass $m_i$ that are located at the coordinates $r_i$ for $i = 1, \ldots, n$. The CG for such a system of particles are, according to [8]:

$$CG = [x_G, y_G, z_G] = \frac{1}{M} \sum_{i=1}^{n} m_i r_i \tag{2.8}$$

## 2.5 Restoring forces

AUVs are designed to be neutrally buoyant in water, according to [14]. A neutrally buoyant underwater vehicle will not rise nor sink if no thrust is applied. The buoyancy of an AUV is given by the restoring forces; gravitational and buoyancy force. The restoring forces on a submerged vehicle like an AUV are, according to [11], determined by the volume of the displaced fluid, the location of the CB, the area of the water plane and its associated moments.

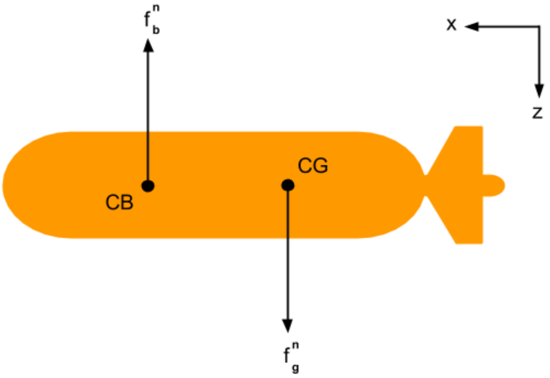

Figure 2.4: The restoring forces acting on an AUV

The restoring forces act in the vertical plane of the NED frame (see Figure 2.4), which according to [11] can be represented by:

$$\mathbf{f}_g^n = \begin{bmatrix} 0 \\ 0 \\ W \end{bmatrix} \quad and \quad \mathbf{f}_b^n = -\begin{bmatrix} 0 \\ 0 \\ B \end{bmatrix} \tag{2.9}$$

According to [11] can the restoring forces and moment vector be expressed in the BODY-frame as:

$$\mathbf{g}(\eta) = \begin{bmatrix} (W-B)\sin\theta \\ -(W-B)\cos\theta\sin\phi \\ -(W-B)\cos\theta\cos\phi \\ -(y_gW - y_bB)\cos\theta\cos\phi + (z_gW - z_bB)\cos\theta\sin\phi \\ (z_gW - z_bB)\sin\theta + (x_gW - x_bB)\cos\theta\sin\phi \\ (x_gW - x_bB)\cos\theta\sin\phi - (y_gW - y_bB)\sin\theta \end{bmatrix} \tag{2.10}$$

Where the $x_g$, $y_g$ and $z_g$ are the coordinates of the CG, while $x_b$, $y_b$ and $z_b$ are the coordinates of the CB.

For a neutrally buoyant vehicle, the weight and buoyancy force are equal [11];

$$W = B \tag{2.11}$$

Consequently, Fossen in [11] states that eith neutrally buoyancy as defined in Equation 2.11, Equation 2.10 becomes:

$$\mathbf{g}(\eta) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -(y_gW - y_bB)\cos\theta\cos\phi + (z_gW - z_bB)\cos\theta\sin\phi \\ (z_gW - z_bB)\sin\theta + (x_gW - x_bB)\cos\theta\sin\phi \\ (x_gW - x_bB)\cos\theta\sin\phi - (y_gW - y_bB)\sin\theta \end{bmatrix} \tag{2.12}$$

Further according to [11], if CB and CG are located vertically on the z-axis, the vehicle is in the stable state (see Section 2.6), the Equation 2.12 becomes:

$$\mathbf{g}(\eta) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ (z_gW - z_bB)\cos\theta\sin\phi \\ (z_gW - z_bB)\sin\theta \\ 0 \end{bmatrix} \tag{2.13}$$

Further if CB and CG coincide, as in the neutral state (see Section 2.6), Equation 2.13 becomes:

$$\mathbf{g}(\eta) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \tag{2.14}$$

## 2.6 Buoyancy, equilibrium states and stability

In water, an underwater vehicle is affected by its weight and the buoyancy force, and the location of CG and CB. The weight and buoyancy is opposite forces, the weight will pull the vehicle downwards, while the buoyancy force pushes the vehicle upwards. The weight and buoyancy force ratio determines how the vehicle floats [14] (see Figure 2.5). If the weight is smaller than the buoyancy force, the vehicle floats to the surface, which is called positive buoyancy. If the weight is greater than the buoyancy force, the vehicle sinks, which is called negative buoyancy. If the weight and the buoyancy force are equal, the vehicle stays motionless in mid-water, which is called neutral buoyancy.

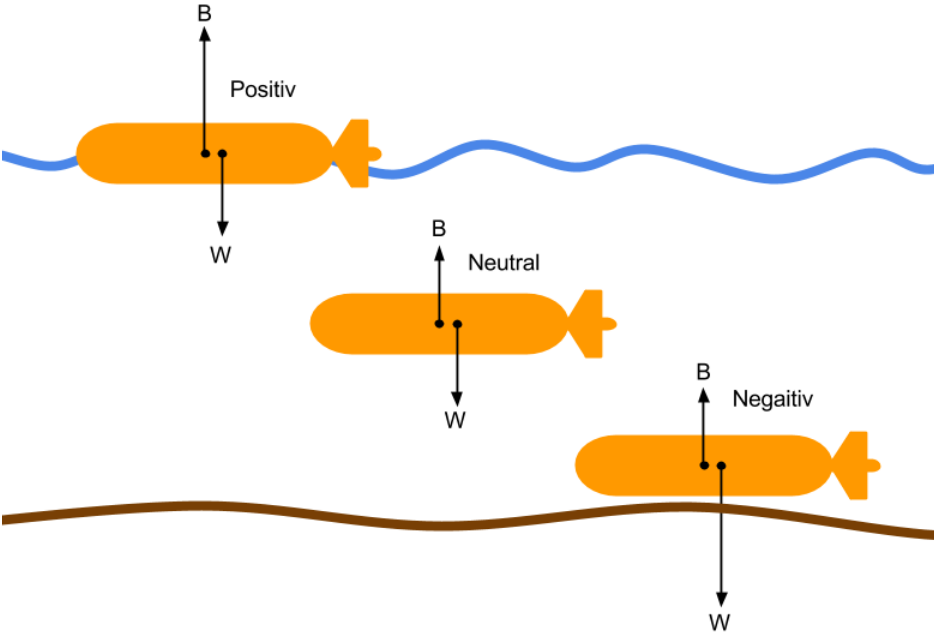

Figure 2.5: The buoyancy states

It is desirable that the AUV is neutrally buoyant or slightly positively buoyant, according to [11]. If it is neutrally buoyant, the AUV will not have to use extra power to stay in mid-water. However, if it is slightly positively buoyant the AUV will, in a case of emergency where it loses power, float back to the surface.

A fully submerged object is neutrally buoyant when the weight of the object, acting through the CG, is equal to the buoyancy force, acting through the CB. For an object with homogeneous mass distribution, the location of the CG will coincide with the CB. However, if the object does not have a homogeneous mass distribution, the location of CG does not coincide with the CB. Depending upon the relative locations of CG and CB, a submerged object can obtain three different equilibrium states, according to [10] (see Figure 2.6).

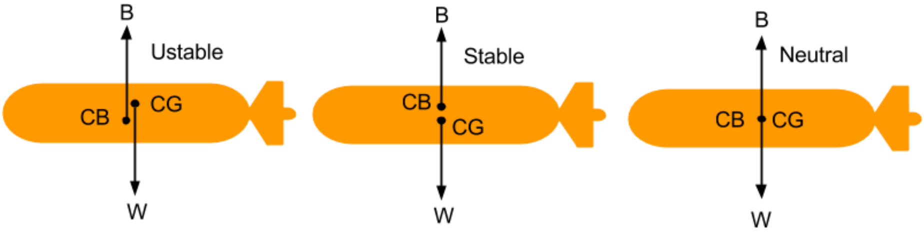

Figure 2.6: The equilibrium states

If the CG is located below the CB the vehicle will have an unstable equilibrium. The weight and buoyancy acting through respectively the CG and CB will cause torques that will try to flip the vehicle. For the opposite situation where CG is located above CB, the object will have a stable equilibrium. When CG and CB coincides the vehicle has a neutral equilibrium. In the three different states of equilibrium, the AUV will behave differently when pushed by currents, applied with thrust or when any external forces acts on it. By giving an AUV a small angular displacement in the water, it will in, according to [10]:

- Unstable equilibrium: the AUV does not return to its original position and increases its displacement further
- Stable equilibrium: the AUV returns to its original position
- Neutral equilibrium: the AUV does not return to its original position, but does not increases its displacement further either

It is desirable that the AUV adopts its new position when affected by external forces as in the case of the neutral equilibrium, which requires the CG and CB coincide. However, according to [14], vehicles where the CG and CB coincide are difficult to control and gives little stability.

Stability is the ability to remain in an upright position [14]. It is desirable to have strong stability, which requires the CG to be located a distance directly under CB. The distance between CG and CB determines how stable the vehicle is, the more they are apart the more stable is the vehicle. This alignment of the CG and CB will put the vehicle in a state of stable equilibrium. If, in addition, the weight and buoyancy force are equal, then the AUV will be in a stable state of equilibrium with neutral buoyancy. This will be the desired state that the system developed in this Master Thesis will strive fulfil.

## 2.7 Ballasting

Surface marine vessels are restricted to operating in the horizontal plane. These vessels therefore only need actuators in the 3 DOFs surge, sway and yaw [11]. The surge, sway and yaw can actively be controlled with thrusters and rudders through guidance systems and motion control systems[1]. The motion in heave and rotations in pitch and roll are normally not actively controlled in these vessels, they are passively controlled by configuration of the vessels' ballast [11].

Underwater vehicles operates in 6 DOFs. Some underwater vehicle are fully actuated. This means that they are actuated in all 6 DOFs and can therefore control its motions and rotations in surge, sway, heave, pitch, roll and yaw [11]. ROVs are often box shaped, which makes room for thruster on all, or most, sides, and ROVs are therefore often fully actuated. This is advantageous as an operator will control the ROV and being able to control all 6 DOF independently makes the controlling easier and more precise operations can be performed.

In contrast to the ROVs, the AUVs are pre-programmed vehicles that normally have a slender-body hull. The slender-body do not allow for actuators in all 6 DOFs. AUVs normally only have rudders and thrusters in the aft and wings at the starboard and port side. With this setup, which the HUGIN 1000 has, only 3 DOFs, surge, sway and yaw, can be actively controlled and they are therefore under-actuated. However, their pre-programmed operations will be able to achieve the desired movements by using the thruster and rudders along with static or active ballasting. The ballasting of the vehicle will affect the three of the DOFs; heave, pitch and roll. According to [11], the ballasting of a vehicle will only change the heave, pitch and roll in which the restoring forces are present.

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[1] For more information on guidance systems and motion control systems see *Handbook of Marine Craft Hydrodynamics and Motion Control* by Fossen, T.I., published by Wiley, 2011

Ballasting is, according to [14], the process of adjusting the buoyancy and trim of an underwater vehicle. The adjustment can be achieved by adding, removing and rearranging weights or floatation devices. When ballasting an underwater vehicle three properties have to be considered; the weight/buoyancy balance, the orientation and the stability.

The weight/buoyancy balance refers to the vehicles ability to float, and can be seen as the heave, and depends on two opposite forces; the downward pulling weight and the upward pushing buoyancy force. The desirable state for the weight/buoyancy balance is neutral buoyancy (see Section 2.6).

The orientation of the vehicle, which is the pitch and roll, depends on the locations of the x- and y-axis parameters of the CG and CB [14]. Any misalignment along the x-axis of the CG and CB will result in the vehicle pitching, while any misalignment along the y-axis of the CG and CB will result in the vehicle rolling. Therefore, the x- and y-axis parameters of the CG and CB should be equal.

The stability of a marine vehicle depends on the locations of the CG and CB. To ensure stability the CG should be positioned directly under the CB, more distance between them gives more stability[2].

The coordinates of the CG and the CB relative to each other and the weight/buoyancy balance determines the state of equilibrium (see Section 2.6). To sum up, the desired properties for underwater vehicles are:

- The weight/buoyancy balance: neutral or slightly positive buoyant, $W \leq B$
- Orientation: $\phi = \theta = 0$ when $CG_{x,y} = CB_{x,y}$
- Stability: CG positioned under CB, some distance apart

### 2.7.1 Ballast error

To be correctly ballasted, which has been defined as a stable state of equilibrium with neutral buoyancy, an AUV must meet the two following requirements:

- the weight and buoyancy forces have be of equal size, this yields neutral buoyancy

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[2] For more information on stability of underwater vehicles see *Underwater Robotics - Science, Design and Fabrication* by Moore, S.W., Bohm, H. and Jensen, V., published by Marine Advanced Technology Education, 2010

- the CG has to be located below the CB, and they have coincide along the x- and y-axis, this yields a stable equilibrium state

A ballast error occurs when the weight of the AUV does not counteract the buoyancy force or when the CG and CB does not meet the conditions mentioned for a stable state. This will make the AUV either positively or negatively buoyant with a tilt. Hence, to ensure that the AUV is neutrally buoyant and in a stable equilibrium state, any ballast error must be corrected by adjusting the ballast. This adjustment can be done by adding or removing weights on the AUV. When adding or removing weights, the total weight and the weight distribution of the AUV will change. Both requirements for correctly ballast must therefore be taken into account when calculating the required ballast adjustment so that an adjustment of the CG does not lead to an error in the ratio of weight and buoyancy or vice versa.

### 2.7.2 Ballasting systems

Ballasting is, according to [14], the process of adjusting the buoyancy and orientations of an underwater vehicle. The adjustment can be achieved by adding, removing and rearranging weights and floatation devices. This adjustment can either be done manually or automatically.

Ballasting systems can either be static and active [14]. Static ballast systems involves performing adjustments of the vehicle's ballast before a dive. According to [14], static ballasting is performed by adding or removing weights and flotation devices. The adjustment will aim to give the vehicle a suitable ballast throughout the entire dive. A static ballast system does no ballast correction during a dive; subsequently the vehicle will have to use thrusters and rudders to achieve depth control. AUVs achieve diving by applying thrust and angling the vehicle downwards with horizontal rudders, fitted at the aft, along with normal vertical rudders, and vice versa when surfacing.

Active ballast systems can actively adjust the ballast of a vehicle during a dive by changing the weight/buoyancy balance, the CG, the CB and/or the orientation [14]. When diving, without applying thrust, the active ballast system will make the vehicle negatively buoyant with a negative pitch angle. When surfacing again, it will be made positively buoyant with a positive pitch angle. These systems are more complex than static ballast systems. However, they will allow the vehicle to move more efficiently without consuming so much energy, and can be used for vertical position control. Vertical position control can be accomplished either by using an active ballast system alone or in combination with other methods for depth control, such as thrusters and rudders.

Active ballast systems utilize different methods to achieve ballast adjustment. These methods include, as listed in [14]:

- Drop weights, which changes the weight: The vehicle is fitted with a weight that makes it negatively buoyant so that it will sink gently. When it has to surface again the weight will be dropped, making the AUV positively buoyant.

- Hard ballast tank, which changes the weight: The vehicle is fitted with rigid-walled pressure-proof, fully enclosed chambers inside or outside the hull. These can be filled and emptied with water by high-pressure pumps. By filling the tanks with water the weight of the vehicle increases.

- Soft ballast tank, which changes the buoyancy: The vehicle is fitted with soft ballast tanks, which are open to the surrounding water through holes in their bottoms. Control valves will lets pressurized air in or out at the top. By filling the tanks with pressurized air the buoyancy of the vehicle increases. This method is not feasible for great depths because the amount of pressurized air needed.

- Oil-filled reservoir, which changes the buoyancy: The vehicle is fitted with flexible bladders outside the hull. When oil from an inside reservoir tank is pumped into these bladders they will expand, consequently the volume increases and therefore also the buoyancy force without adding weight. When the oil is pumped back into the internal reservoir tank again the buoyancy force decreases.

- Trim tank, which adjusts the pitch without changing the weight/buoyancy balance: The vehicle is fitted with one tank in the fore and one in the aft. A liquid is moved between the two tanks to shift the weight and consequently adjusting the pitch.

- Shifting weight mechanisms, which adjust the pitch or roll without changing the weight/buoyancy balance: The vehicle has a system that mechanically shifts significant weight between the fore and aft inside the hull to adjust the pitch, or between the starboard and port side to adjust the roll.

## 2.8 Optimization problems

Optimization is the process of finding the best solution from a set of feasible variables. According to [15], an optimization problem must be defined with an objective and any constraints that exist. The objective can be expressed as an objective function, $f$, of a vector of variables, $x$. The objective function will be minimized or maximized while subjected to constraints, $c$. The constraints can either be equalities or inequalities, which the vector $x$ must satisfy.

An optimization problem can be formulated as follows:

$$\begin{aligned} \min_{x \in R^n} \quad & f(x) \\ \text{s.t.} \quad & c_i(x) = 0, i \in \mathcal{E} \\ & c_i(x) \geq 0, i \in \mathcal{I} \end{aligned} \tag{2.15}$$

Optimization problems can be either linear or nonlinear. When the objective function and the constraints are linear, the problem is a linear programming problem. In contrast, if the objective function or the constraints are nonlinear, the problem is a nonlinear programming problem.

In [15] the optimization problems are categorized based on whether they are continuous or discrete. Continuous optimization problems have objective functions that are continuous, and the vector of variables is drawn from an infinite set of real numbers [15]. By contrast, in discrete optimization problems the vector of variables is drawn from a finite set. A type of discrete optimization problems are integer programming problems where the vector of variables are constrained to integers [15].

The integrality constraints are a set of integers $x_i \in \mathbb{Z}$. If all of the variables are required to be integers, then the problem is an integer programming problem [15]. Further, if the objective function and the constraints (other than the integer constraints) are linear, then the problem is an integer linear programming problem. Integer programming problems can, according to [15], be formulated as:

$$\begin{aligned} \min_{x \in R^n} \quad & f(x) \\ \text{s.t.} \quad & c_i(x) = 0, i \in \mathcal{E} \\ & c_i(x) \geq 0, i \in \mathcal{I} \\ & x_i \in \mathbb{Z} \end{aligned} \tag{2.16}$$

Optimization problems can be solved with optimization algorithms, which according to [15] are interactive. According to Nocedal and Wright in [15], a good algorithm should be robust, efficient and accurate. These properties may conflict, and different algorithms make various tradeoffs between them giving them different qualities.

Linear programming problems can efficiently be solved even in a worst case scenario with several different algorithms that are robust, efficient and accurate. In contrast, integer programming problems and mixed integer programming problems are NP-hard[3].

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[3] For more information about NP-hard problems see *Introduction to Algorithms* by Cormen, T.H., Leiserson, C.E., Rivest, R.L. and Stein, C., published by The MIT Press, Cambridge, Massachusetts, 2009, 3rd edition, page 1069

# Chapter 3

# The HUGIN 1000

This chapter presents the HUGIN 1000. The system developed in this Master Thesis was initially commissioned and designed for HUGIN 1000. HUGIN 1000 is produced by the Norwegian company Kongsberg Maritime. They produce several different AUVs for both civilian and military use. Kongsberg Maritime's AUVs include the HUGIN, MUNIN, REMUS and SEAGLIDER lines [2]. These AUVs have different capabilities and therefore different areas of application.

One of the AUVs in the HUGIN line is the HUGIN 1000. According to [1], this vehicle is used for mapping the ocean floor for the oil industry and for mine clearance and reconnaissance for the military. To enable these different types of applications, HUGIN 1000 carries several payloads with different sensors and processing devices. HUGIN 1000 is, according to [3], built with a three-module structure; a standardized fore and aft sections and one or two modular mid-sections that can be configured with a variety of payloads.

According to [3], the design goals for HUGIN 1000 were to provide:

- Maximum data quality
- Highly efficiency in operations
- Robust and reliable in operations
- Complete AUV concept for civilian and military usage

The system developed in this Master Thesis will attempt to enhance the second and third design goal by making the AUV more energy efficient and controllable through correct ballast.

Kongsberg Maritime has provided several specific vehicle values for use in the development of the software tool, which are presented in Table 3.1. HUGIN 1000 is the only available AUV in the software tool developed in this Master Thesis, however, it will be easy to add new AUVs to the system.

| Property | Value |
|---|---|
| Diameter | 0.75 m |
| Length | 5.23 m |
| Weight in air | 1 498 kg |
| Weight in water | -65 kg |
| Center of buoyancy | [-157.8, 0.57, -11.38] mm |

Table 3.1: Technical specifications for HUGIN 1000

Figure 3.1: The HUGIN 1000[1]

HUGIN 1000 can move in all 6 DOFs; surge, sway, heave, pitch, roll and yaw (see Section 2.1). However, only surge, sway and yaw is actively controlled in the HUGIN 1000 with a thruster and rudders mounted in the aft. Heave, pitch and roll are passively stabilized before a mission by adjusting the ballast of the AUV. The ballast adjustments of HUGIN 1000 are performed by adding or removing weights from four specific points where weights can be added without changing the volume of the vehicle.

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[1] The figure is the courtesy of Kongsberg Maritime at `http://www.km.kongsberg.com/ks/web/nokbg0240.nsf/AllWeb/6A524BCD3B1DFEE4C1257911002C6809?OpenDocument`

It is desirable that the AUV is neutrally buoyant and in a stable equilibrium (see Section 2.6), which means that the AUV will have no heave motion or pitch and roll angles unless thrust or rudder angles are changed. The heave motion depends on the weight/buoyancy balance of the AUV. The pitch and roll rotations depend on the location of the CG relative to CB, which depends on how the weight of the AUV is distributed. The objective of the system developed in this Master Thesis for HUGIN 1000 is to find the ballasting configuration that gives the desired stable state of equilibrium with neutral buoyancy.

## 3.1 Points of adjustment and available weights

To adjust for ballast error, the HUGIN 1000 has four points for adding adjustment of weight; one at the fore starboard side, one at the fore port side, one at the aft starboard side and one at the aft port side. The position of these points are illustrated in Figure 3.2 and their exact positions are given in Table 3.2 where all the values are defined according to the definition in Section 2.1.

| Adjustment points | Location | Coordinates |
|---|---|---|
| Point 1 | Fore/starboard | [1 032.50 325.00] mm |
| Point 2 | Fore/port side | [1 032.50 -325.00] mm |
| Point 3 | Aft/starboard | [-493.41 325.00] mm |
| Point 4 | Aft/port side | [-493.41 -325.00] mm |

Table 3.2: The positions of the points of adjustment

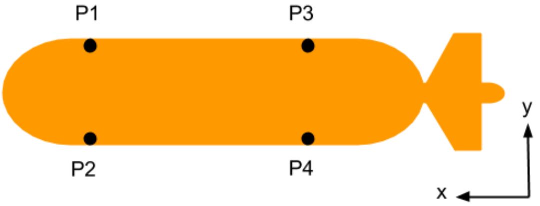

Figure 3.2: The positions of the points of adjustment

The weights have to be added manually by a human operator. By adjusting these weights the ballasting of HUGIN is changed. It is assumed that only the weight and the CG will change by adjusting the weights. The buoyancy of the AUV and the CB are assumed to be fixed because the volume is not changed since the weights are added inside the hull.

The weight of HUGIN 1000 can be increased by adding a standard set of weights with different masses, $W_{4,8kg} = 4,8$ kg, $W_{2,4kg} = 2,4$ kg and $W_{1,2kg} = 1,2$ kg.

When calculating the needed adjustment, there must be a balance between adjusting the weight so that it equals the buoyancy force and shifting of the CG towards the CB. This balance is constrained by the three available weight sizes. To gain the correct ballast, a combination of weights will have to be added at the four points of adjustment.

## 3.2 Data collected during missions

During its missions, HUGIN 1000 collects large amounts of data through several different sensors. Kongsberg Maritime has provided one set of such mission data for analyses and use in this Master Thesis. These data will not be presented, only mentioned when necessary, since Kongsberg Maritime does not want the data to be shared in this paper or be published.

The mission data are stored in several txt-files. The mission data are loaded into the system during the post mission mode (see Section 5.2.2), where the data are processed and the necessary data are stored in the ballasting file (see Section 5.5.2). The data needed for the ballast adjustment calculations are depth, temperature, salinity, pitch and roll. The temperature and salinity are measured with a Doppler instrument and a CTD instrument[2]. In the calculation of the current water density, the average of the two measurement methods for salinity and temperature are used. The calculation of the water density is a crucial part of finding the correct ballast adjustment (see Section 4.5).

To check if the AUV is able to reach the desired depth, the commanded depth from the file of miscellaneous data, are compared with the actual measured depth that is stored in the depth file (see Section 5.3.1). The depth file also contains data on the pitch angle, $\phi$. The pitch is measured with both the navigation system and a magnet compass. However, the magnet compass is less accurate, therefore only the measurements from the navigation system are used. In addition to the data on measured pitch, the control input for pitch and the measured

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[2] CTD is an oceanography instrument that determines the water's conductivity, temperature and depth [16]

depth can used to determine if the pitch is correct (see Section 5.3.2).

To determine if the roll angle, $\theta$, is correct (see Section 5.3.3), several files of different data are used. A file containing navigation position data has data on the measured roll angle. In addition, data on the propeller speed and the forward velocity are collected during the mission and stored in respectively a file of miscellaneous data and a file of velocity data.

The ballast adjustments aim to make the AUV correctly ballasted during the whole mission. However, the depth, temperature and salinity are not equal throughout an entire mission. The pressure is lower and temperature is higher when the AUV is near the surface in the start or end of a mission. These data are not representable for the main part of the mission, which takes place in deeper water. The most crucial part of the mission, in respect to efficient ballasting, is the operational part after the diving and before the surfacing. It is therefore only these data that are used in the calculations of ballast adjustment, while the data collected during the diving and surfacing are excluded. It is assumed that the period the AUV operates at the main operation depth is between 0.4 and 0.6 times the length of the whole data set.

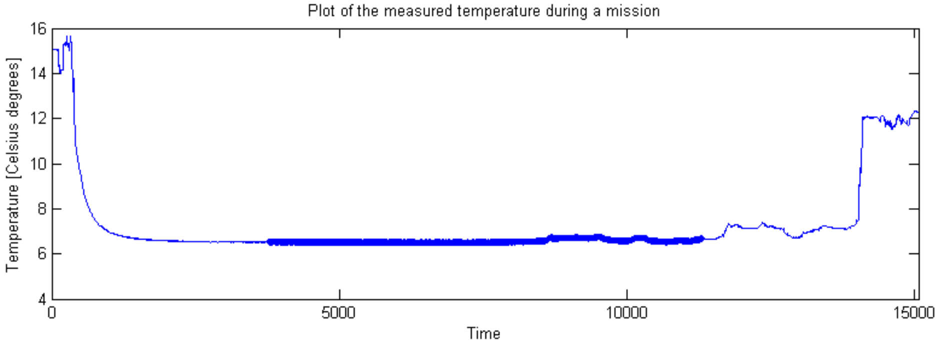

Figure 3.3: Plot of temperature data collected during a mission

Figure 3.3 illustrates the point of using only the data from the middle part of the data set; the thin line is the average temperature data from the Doppler and CTD instrument collected during the whole mission, while the thick line is the set of data that is used from the middle part. By viewing this plot, it can be seen that the temperature is considerably lower at the main operation depth.

# Part II

# THE SYSTEM AND ITS DESIGN

# Chapter 4

# Design issues and decisions

Through the work with the Master Thesis, several issues and problems have emerged. The author has had to make several decisions concerning to development of the system. Some of these are presented in this chapter along with their solution.

## 4.1 Programming language

One of the first major decisions that had to be made was which programming language to use when implementing the system devolved in this Master Thesis. The two programming languages that were considered were C++ and Matlab. When developing new software tools, Kongsberg Maritime tend to use Matlab to make prototypes and to analyze the new software's performance[1]. Matlab is more suitable than C++ for mathematical calculations and for analyzing large amounts of data. However, Matlab is a lot slower than C++ and is therefore not suited for real time execution. C++ is therefore widely used by Kongsberg Maritime for systems running in real time.

For the system implementation in this Master Thesis, Matlab has been used. This decision was based on the premises of the system, which was that the system is not going to run in real time, only before and after missions. Hence, the speed

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[1] According to Øystein Lurås, the author's uncle, who works at Kongsberg Maritime

of the programming language is not an issue. Moreover, the system will have to handle large amounts of data and do several numerical calculations involving vectors and matrices. In view of this, Matlab was chosen for the developing the system.

## 4.2 The weighing method

Today, Kongsberg Maritime has no method for weighing their HUGIN 1000. They do however have a crane for moving the AUV around on land. To get the weight of the AUV, weight cells could be attached to this crane. To gain information about the weight distribution, two ropes could be attached around the AUV, one in the fore and one in the aft, and each end of the two ropes can be fitted with a weight cell. Then each of the weight cells would give the weight of the section that it supports through the rope. This will give a measurement of how the weight is distributed along the x- and y-axis. Figure 4.1 illustrates this setup seen from one side. This will be the method used for weighing the AUV.

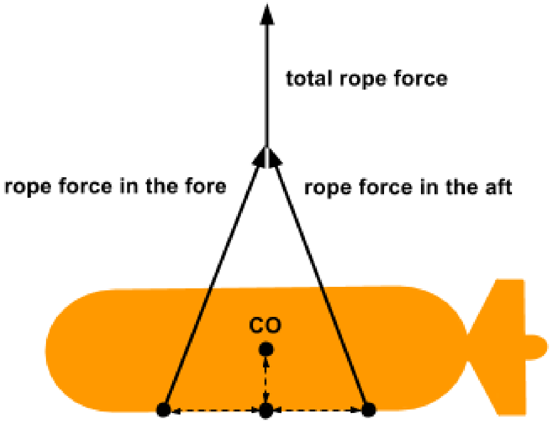


Figure 4.1: Weighing with four suspension points when the AUV is seen from the left side

One weight cell on each rope and on the main rope will give five measurements:

- the mass of the fore starboard section, $m_1$, located $r_1$ from the CO
- the mass of the fore port section, $m_2$, located $r_2$ from the CO
- the mass of the aft starboard section, $m_3$, located $r_3$ from the CO

- the mass of the aft port section, $m_4$, located $r_4$ from the CO
- the mass of whole AUV, $M$

In the first mission mode the CG will be calculated based on these measurements. How this is done is explained in Section 4.4.

The proposed weighing method requires weight cells that can be attached as a direct extension of the rope so that the measured weight is the actual force pulling on the rope. Therefore, the recommended weight cell type is a hanging crane scale that is easy to use and not too expensive. Hanging crane scales are available with different weight restrictions. For HUGIN 1000 the weight cells should tolerate at least two tons each in case one or more break while supporting the HUGIN 1000. If desired, one weight cell for measuring the total weight should tolerate three tons.

## 4.3 The first mission mode

Kongsberg Maritime requested two modes of operation in their ballasting system: a pre mission mode and a post mission mode. The pre mission mode should base its calculations on detailed mission data that the post mission mode has processed and stored. However, there are no data available the very first time the system is used. One solution, which would be simple and quick, would be to just launch the AUV, assuming that any ballast error would not cause the AUV to fail or crash. However, this would most likely sacrifice the first mission; no operations demanding a certain level of performance from the AUV could be conducted because of the possible severe ballast errors. It was therefore concluded during the work with this Master Thesis that it was beneficial to implement an additional mode that could be used before the first mission, although this mode would require more time on land before the first launch. This mode, called the first mission mode, handles the calculations of ballast adjustments based on the relatively little information that are obtained with manual measurements.

In the first mission mode, several user inputs are needed to set up a new AUV configuration. The user will start by selecting the AUV type, area of operation and type of water, which will be stored in a special ballasting file (see Section 5.5.2). Then the user will be asked for some weight measurements and rope locations (see Section 4.2), which will give an indication of the weight distribution. One of the issues that the first mission mode must handle is the first time calculation of the water density without the mission data about the temperature or the salinity of the water. To keep the first mission process simple and quick, the solution is to base the calculation on simple manual measurements and assumptions.

The user will, in the first mission mode, be asked to enter a measured water temperature and select the type of water:

- The water temperature could just be a single temperature reading of the water in which the first mission will take place. Since the temperature then will be measured near the surface, this measurement might not be accurate. The temperature down on the depth of the operation may differ significantly.

- The salinity will be an assumption based on the type of water in which the first mission will take place. The user will have to select the level of salinity from a table of average salinity levels of different waters (see Table 2.1).

Due to the inaccuracy of these measurements, the calculation of the water density in the first mission mode will be less accurate then in the pre mission mode where accurate mission data in known. However, the calculation is sufficiently accurate for the first mission, where the aim is only to make sure that the ballast error is small enough to not affect the operations of the AUV too much.

## 4.4 Calculation of the center of gravity

The calculation of the CG is a key issue for the system. In the first mission mode, the CG will by calculated based on theory presented in Section 2.4 and the weighting method presented in Section 4.2. The weight cells, proposed in the weighting method, will give the weight, not mass. The measured weight cannot be directly used, the weight will have to be divided by the gravitational force to get the mass that will be used in the calculation of the CG.

The CG will be calculated as a system of particles because of the payloads in the AUV, which have different masses and give the AUV a non-linear and non-homogeneous mass distribution. This calculation will be a little inaccurate, however, it will be sufficiently accurate for the first mission. To ease the calculations and keep the necessary measurements to a minimum, the system will be considered to have four particles, $P_i$ for $i = 1$, 2, 3 and 4, each with a mass $m_i$ that are located at the coordinate $r_i$ for $i = 1$, 2, 3 and 4. The CG for a system of particles are:

$$
\begin{aligned}
CG = [x_G, y_G, z_G] &= \frac{1}{M}\sum_{i=1}^{4} m_i r_i \\
&= \frac{1}{M}(m_1 r_1 + m_2 r_2 + m_3 r_3 + m_4 r_4) \qquad (4.1)
\end{aligned}
$$

Where the mass $m_1$ is the mass of the fore starboard section, $m_2$ is the mass of the fore port section, $m_3$ is the mass of the aft starboard section, $m_4$ is the mass of the aft port section, and $M$ is the total weight. The $r_1$, $r_2$, $r_3$ and $r_4$ are the distance from the CO to the suspension points for respectively the fore starboard, fore port, aft starboard and aft port side according to weighting method presented in Section 4.2. It is assumed that the distance $r_i$ in the y direction are 0.25 m from the starboard side and -0.25 m for the port side, while the distances in x direction are decided by the user when they attach the ropes for weighing. The user gives the x directions as inputs.

## 4.5 Calculation of water density

Another key issue is the calculation of the water density. Many of the calculations necessary to identify ballast errors depend on the water density. The calculation of the water density is based on the calculator implemented at web site ”Water Density Calculator” [4]. The site refers to an article called ”A new high pressure equation of state for seawater” [13]. This article presents how the water density can be derived based on the temperature and salinity of the water, and the pressure at the depth of operation.

The water density calculator, in this Master Thesis, will be based on the calculator at [7]. The calculator was tested with several different inputs and its calculated outputs were checked against the graph in Figure C.1. The calculator proved to be accurate and was therefore used for the implementation of a water density calculator in this system. By viewing the page source code of [7], the HTML was converted to Matlab code and modified to fit the input used in the system developed in this Master Thesis. The modified Matlab code can be seen in Appendix C.3.

The water density is calculated based on the salinity, temperature and pressure of the water. As the pressure is never directly measured, only the depth is. The pressure therefore has to be calculated using Equation 2.3. This equation depends on the depth, gravitation acceleration and water density. The water density is not known and has to the calculated too. The precise calculation of water density depends on the pressure, which is still unknown. However, the water density can be calculated without the pressure, and then the pressure could be calculated with this water density. The resulting pressure could then be used in the accurate water density calculation. However, using the accurate water density calculation with the calculated pressure will not yield a better result than the calculation without pressure, since the pressure is already calculated with the less accurate method. Therefore, the depth and pressure are not used when calculating the water density, only the salinity and temperature are used, which give relatively accurate results, only 0.45 % differs between the water density without pressure and with pressure at 1 000 m (see Figure C.1 and Table C.1).

In the first mission mode where the temperature and salinity of the water are based on simple manual measurements and assumptions, the calculation will be less accurate then in the pre mission where accurate mission data in known. Nevertheless, it is sufficiently accurate for the first mission.

# Chapter 5

# The system

The system, which has been designed, developed and implemented in this Master Thesis, will be presented in this chapter. The system is a software tool for automatic identification of ballast errors in AUVs. It was designed to meet Kongsberg Maritime needs, and will be the result of their requirements and wishes, and confined by the limitations that concerns their AUV (see Section 1.2.1). The software tool will replace the manual process of ballasting the AUV that is used by Kongsberg Maritime today. The ballasting adjustments will strive to produce a stable state equilibrium with neutral buoyancy in the AUV, and this is the goal of the developed system.

Overall, the system is actually semi-automatic. It automatically identifies ballast errors and maps the required adjustments, however, it requires a human operator to perform the actual adjustments. Consequently, the system is based on static ballast adjustments (see Section 2.7.2) and does therefore not run in real-time. The system will only be ran before and after missions with different modes of operation, which include the first mission mode, the pre mission mode and the post mission mode (see Section 5.2). Together these modes performs the two main objectives of the system; identifying any ballast errors based collected mission data and calculating required ballast adjustment (see Section 5.3 and 5.4).

## 5.1 System specification

Kongsberg Maritime commissioned a system for automatic identification of ballast errors for their HUGIN 1000. They wanted a system that could replace the current, manual ballasting process, which requires skills and experience, and is time-consuming. They presented requirements and some wishes for the behavior and performance of the system. Some of their requirements have been modified during the work with the system by the author. These modifications were made to improve performance of the system. One modification concerned the number of operational modes (see Section 4.3). The specifications listed below are a combination of Kongsberg Maritime's wishes and requirements, and the author's views on which requirements that should be included.

The specifications for the system are accordingly:

1. The system automatically identifies the required vehicle ballasting before missions and maps suitable ballast adjustments for a human operator.
2. The system has three modes of operation:
   (a) The first mission mode identifies necessary changes in ballast based on vehicle measurement and readings from weight cells.
   (b) The pre mission mode calculates necessary changes in ballast based on vehicle data collected during a mission.
   (c) The post mission mode identifies ballast errors based on vehicle data collected during a mission.
3. The first mission mode of the system minimizes the need for re-doing the ballasting before every mission. Some corrections are accepted.
4. The system includes a method for weighing the AUV, giving measurements for calculating ballast adjustments before the first mission.
5. The system stores previous calculations of the weight adjustment, which will be used to improve the ballasting of the AUV.
6. The system adjusts the ballast to achieve a stable equilibrium with neutral buoyancy. The system prioritizes ballast adjustments as follows in decreasing order:
   (a) The correct weight/buoyancy balance
      i. Avoid negative buoyancy
      ii. Avoid positive buoyancy

   (b) The correct orientation
      i. Correct pitch angle, the CG and the CB coincide along the x-axis
      ii. Correct roll angle, the CG and the CB coincide along the y-axis
   (c) The stability
      i. The CG has to be located under the CB
      ii. Some distance between CG and CB along the z-axis

7. The system should significantly improve the ballasting of the AUV, the ballast errors limited to:
   (a) Depth error is +0.1 m and -0.0 m
   (b) Weight/buoyancy error is -1.2 kg and +0.0 kg
   (c) Pitch error is ± 0.5 degrees
   (d) Roll error is ± 0.1 degrees
8. The system is designed to make the ballasting process significantly faster than doing it manually:
   (a) The user interactions are kept to a minimum.
   (b) When user interactions are needed, they are explained with clear instructions to avoid operator errors.
9. The system aims to be user friendly:
   (a) Easy and quick to learn.
   (b) Requires little or no training and experience to master.
   (c) Simple to use.
10. The system is modular and general, it can be expanded to provide identification of errors and adjustments for different AUV, and different parts of the calculations can be modified easily.

The specifications provided by Kongsberg Maritime are 1, 2b, 2c, 7, 8 and 10, while specifications 2a, 3, 4, 5, 6 and 9 are derived by the author. Several of the points mentioned in this specification will be elaborated on in the following sections.

## 5.2 System modes

The system identifies ballast errors in accordance with the specifications listed in the Section 5.1. This section will give an overview of the system with its three mission modes; the first mission mode, the pre mission mode and the post mission mode. The sequence in which the system is executed, as seen in Figure 5.1, starts with a new AUV or an AUV with a new payload configuration that will be ran with the first mission mode. The first mission mode was included in addition to the pre mission and post mission mode that Kongsberg Maritime requested (see Section 4.3).

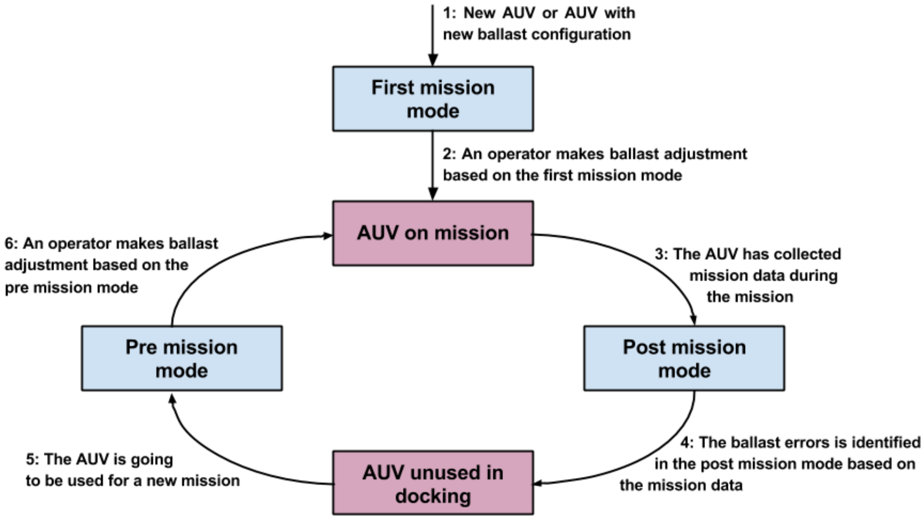


Figure 5.1: The sequence of the system modes

The system does not run during missions. It is only ran before and after as a tool for identifying ballast errors that have to be corrected. The first mission mode is only used before the very first mission. Later the pre mission mode will be used before missions to improve the ballasting of the AUV. The post mission should be ran after every mission to make sure that all the needed data are stored for later use. Figure 5.2 shows a simple state diagram of the system.

The first mission mode identifies ballast errors based on vehicle measurements and readings from weight cells (see Section 4.2), which it uses to calculate the required weight adjustment. The pre mission mode calculates the required weight adjustment based on the errors identified in the post mission mode and vehicle data collected during the last mission. These data include readings of pitch, temperature, salinity, etc. collected during a mission. The post mission mode identifies ballast error based on collected mission data and stores the data in a file (see Section 5.5.2), which will be used to calculate the required ballast adjustment in the pre mission mode.

### 5.2.1 First mission mode

When a new AUV should be ballasted for the first time, the first mission mode will be used to calculate and map necessary ballasting adjustments based on some user inputs. These user inputs include the type of AUV, area of operation and the weight distribution. The weight distribution is found by using the weighing method presented in Section 4.2 and based on the calculations explained in Section 5.4.1, the system will determine whether the AUV has a ballast error or not.

If there is a ballast error, the required adjustments will be mapped for a human operator, which has to perform the adjustments by adding weights to the AUV. The mapping will tell the operator at which points of adjustments weights have to be added and how much needs to be added. When the adjustment is finished, the first mission mode will create the ballasting file (see Section 5.5.2) and store some of the results from its calculations. This ballast adjustment will not yield the optimal ballast configuration. However, it will give a satisfying ballast. It will make sure that the AUV has an adequate performance so that the costumer will not waste their first mission with the AUV.

### 5.2.2 Post mission mode

The post mission mode will load data collected during the mission (see Section 3.2). It will search for specific data that can be used to improve ballasting. The interesting data are the measured temperature and salinity, the measured and commanded pitch, measured roll, the measured and commanded depth, the measured propeller speed and the measured forward velocity of the AUV. The depth, pitch and roll data will be used to identify any errors in the AUV's ballast (see Section 5.3). After processing the data and identifying any ballast errors, the results and some other data will be stored in the ballasting file.

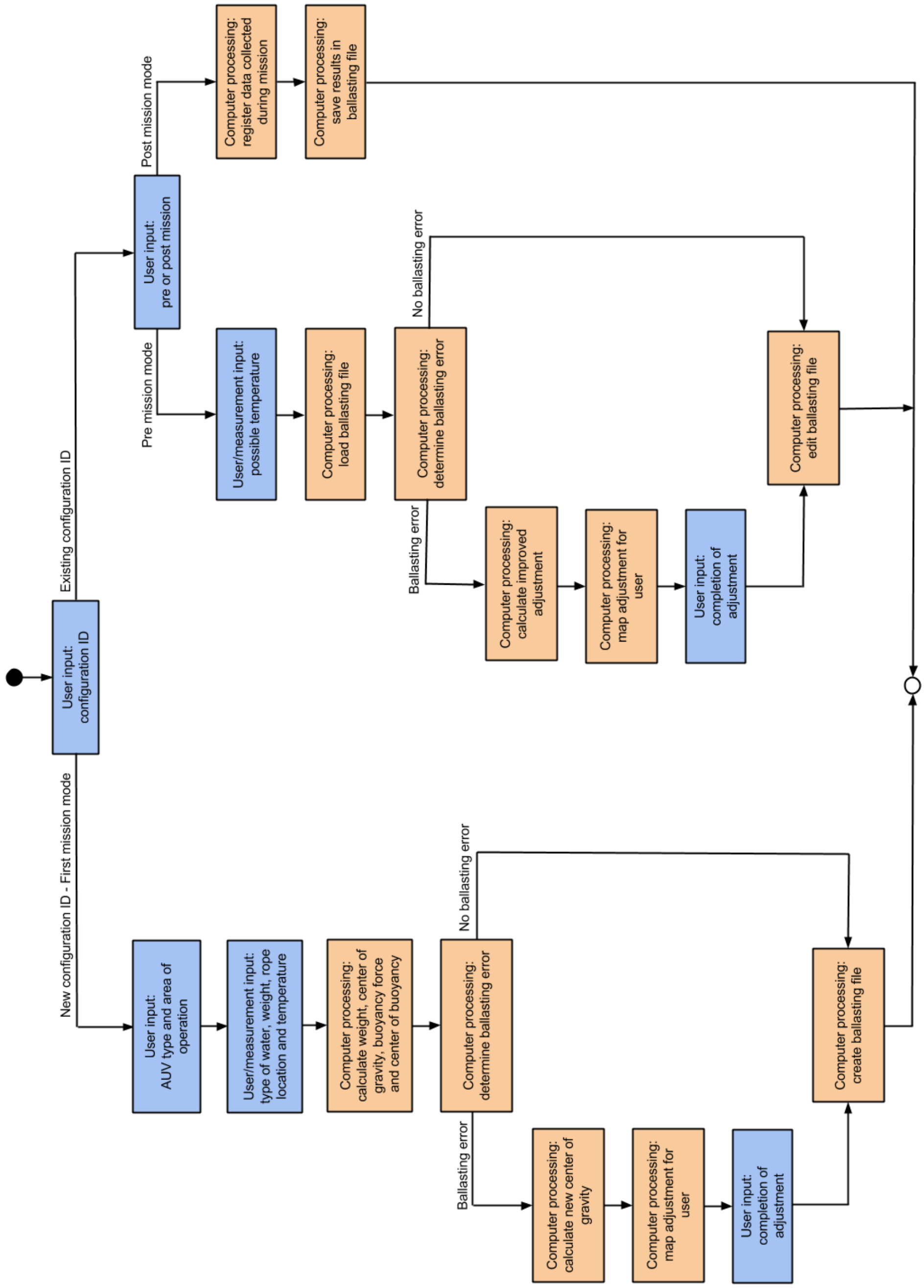


Figure 5.2: State diagram of the system

### 5.2.3 Pre mission mode

Before the second and later missions, the pre mission mode of the system will be used. During missions the AUV will collect data, which the post mission mode will process and store in the ballasting file. The pre mission mode starts by loading the ballasting file with the previous calculations and collected mission data. If a ballast error has been found, these data will be used to calculate new ballast adjustments that should improve the performance for next mission (see Section 5.4.2). The system will then map the required adjustments for the four points of adjustments. The system will instruct the user on which weights to add where. When the adjustment is finished, the system will add the results of the calculations in the ballasting file.

## 5.3 Identification of ballast errors

One of the system's main purposes is to identify any ballast errors present in an AUV. Based on the identified errors, the system will proceed to calculate the necessary adjustments (see Section 5.4). How the ballast errors are found and identified is an important aspect of the system. The performance of the system relies on its ability to identify any ballast errors and to which degree the system is able to calculate suitable adjustments (see Section 5.4). How ballast errors are identified is presented in this section. According to Section 2.7.1, a ballast error occurs when the weight of the AUV does not counteract the buoyancy force or when the CG is not located directly below the CB. Different approaches are used to check for these conditions in the two mission modes that are responsible for identifying ballast errors; the first and post mission mode (see Section 5.2).

In the first mission mode, the user will input weight measurements, and based on these measurements and other known values the weight, buoyancy, CG and CB will be calculated (see Sections 5.4.1 and 4.2). The first mission mode will then determine suitable adjustment based on its own findings.

The ballast adjustments determined in pre mission mode is based on the findings of the post mission mode. The post mission mode loads the mission data from the vehicle and identifies ballast errors based on these data. Both the weight/buoyancy balance and the orientation of the vehicle are checked. How the weight/buoyancy balance is checked will be presented in Section 5.3.1. In this case, the CB and CG cannot be directly compared to check the orientation as they are not known. To check the orientation, the measured pitch and roll angles of the AUV that have been collected during missions will be studied. If the pitch and roll angle of the AUV is zero when laying horizontal in the water the AUV then it is assumed that the CG and CB coincide along the x- and y-axis. A more detailed explanation of how the orientation is checked will be presented in Sections 5.3.2 and 5.3.3.

### 5.3.1 Checking for errors in weight/buoyancy balance

A weight/buoyancy balance error, also called weight/buoyancy imbalance, means that the weight of the vehicle is not equal to the buoyancy force acting on the vehicle. An error in the weight/buoyancy balance will result in the vehicle becoming either positively and negatively buoyant (see Section 2.6). Two different approaches can be used to determine if there is a weight/buoyancy imbalance:

1. The weight and the buoyancy force can be calculated based on known measurements, and can then be compared to see if they cancel each other out.
    (a) If the weight is greater than the buoyancy force, the vehicle will be negatively buoyant.
    (b) If the weight is smaller than the buoyancy force, the vehicle will be positively buoyant.
2. The depth commanded and the measured depth from the mission data can be compared to see if the vehicle is able to reach and hold the desired depth.
    (a) If the vehicle is not able to reach down to the commanded depth, the vehicle is positively buoyant.
    (b) If the vehicle is not able to get up to the commanded depth, the vehicle is negatively buoyant.

In this system both approaches will be utilized; the depth checking approach will be used to determine if there is a weight/buoyancy imbalance, while the weight/buoyancy comparing approach will be used to calculate the size of the needed adjustment.

#### The weight/buoyancy comparison approach

The weight/buoyancy comparison approach uses the measurements of salinity and temperature from the vehicle's mission data to calculate the buoyancy force that the vehicle experienced on its mission. This approach takes into account that the buoyancy force acting on the vehicle changes when the salinity and temperature of the water change.

The buoyancy force is calculated using Equation 2.5, and the result is then compared with the calculated weight of the vehicle. If the weight is greater than the buoyancy force, the vehicle is negatively buoyant and requires less weight. Vice versa, if the weight is smaller than the buoyancy force, the vehicle is positively buoyant and requires more weight.

The drawback with this approach is that it is based on theorized calculations, and the result is not directly measurable. However, this approach will, if assumed correct, give an actual value of the needed weight adjustment if a weight/buoyancy balance error is detected. This is why this approach will be used to calculate the needed adjustment after the depth comparison approach has been used to detect a ballast error. The size of the required adjustment can be calculated by subtracting the weight, W, from the buoyancy force, B. This gives the weight difference. By dividing this by the gravitational acceleration, the mass difference is found:

$$|B - W| = W_{dif} \tag{5.1}$$

$$m_{dif} = \frac{W_{dif}}{g} \tag{5.2}$$

How the required mass difference, $m_{dif}$, is divided between the four points of adjustment is explained in Section 5.4.

### The depth comparison approach

The depth comparison approach does not consider the water properties, it will utilize the depth measurements from the mission data to check for a weight/buoyancy balance error. A weight/buoyancy error can be detected by comparing the commanded and measured depth of the vehicle. Any deviation in the two values indicates that the vehicle is not able to reach and maintain the desired depth. By subtracting the value of the measured depth from the commanded depth for each time step, the average of the resulting values will give an indication of the deviation in depth.

The advantage of this approach is that it is based on actual vehicle measurements from missions and a simple comparison calculation; there are no assumptions or simplified theoretical calculations involved. It will with great accuracy be able to determine if there is a weight/buoyancy balance error. The drawback is that it does not provide any concrete value of the weight adjustment that is needed, it only gives an indication of whether weight must be added or removed.

By viewing the plot in Figure 5.3, it can be seen that the measured depth is slightly above the commanded depth (the greater value, the deeper water). An algorithm has been derived for identifying this depth error, the implemented code can be seen in Appendix D.1. This algorithm will yield a positive value with the data showed in Figure 5.3. A positive value indicates that the AUV does not reach down to the commanded depth, which means that the AUV is to light. A negative value indicates that the AUV is too heavy.

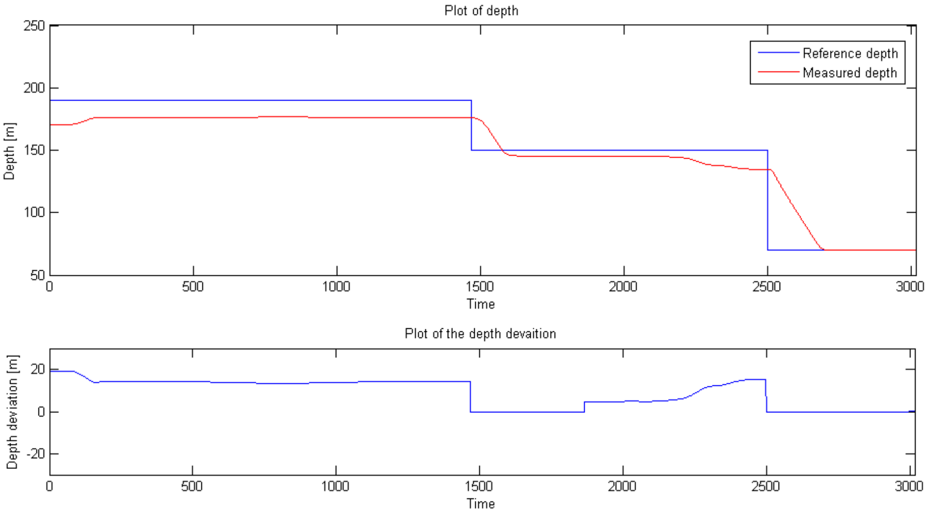


Figure 5.3: Plots of the commanded and measured depth, and the deviation in weight/buoyancy balance from the comparison check of depth

As seen in the code in Appendix D.1, data immediately after a step is not used. This is because of the dynamic response of the system, the vehicle is not immediately able to adopt the new desired depth. The vehicle needs time to move to its new desired depth. Figure 5.4 shows the depth step response of the vehicle. It can be seen that the vehicle needs approximately 150 time steps to adopt the new stable depth 40 meters above the previous commanded depth. As the vehicle moves toward its new position, there will be a significant deviation between commanded and measured depth. Using these deviations in the calculation of weight/buoyancy imbalance is not productive. This is why the data immediately after a step is not used.

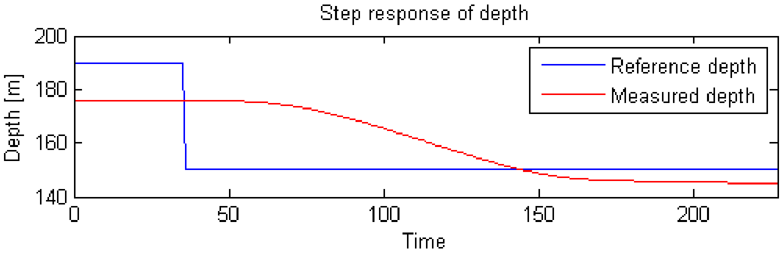


Figure 5.4: Plot of a step in commanded depth and the following measured depth of the vehicle

The depth checking approach will be used to determine if there is a weight/buoyancy balance error because of its more reliable approach of detecting errors as it is based directly on actual vehicle data.

### 5.3.2 Checking for errors in pitch

Pitch is the rotation about the y-axis (see Section 2.1 and Figure 2.2). This rotation is affected by the vehicle's weight distribution along the x-axis. If there is more weight in the fore, the AUV will tilt with its nose downwards and the pitch will be negative. If there is more weight in the aft, the nose will tilt upwards and the pitch will be positive. A pitch error will result in unwanted, additional drag since the vehicle will show more of its side towards the direction of motion. The valid deviation in pitch is ± 0.5 degrees.

The AUV collects data during missions about its pitch angle, both measured pitch and commanded pitch, and about its depth, both measured depth and reference depth. Figure 5.5 shows plots of the measured depth and reference depth and the measured pitch and command pitch during a mission. Two different approaches can be used to determine whether the AUV has a pitch error; comparing measured and commanded pitch or checking pitch at a stable depth.

The plots in Figure 5.5 show data from the whole mission. However, to check for pitch error only the middle section of the data collected is used, as explained in Section 3.2. These data give an indication of how the AUV behaves during the actual execution of its mission tasks. It is during this stage of the mission that errors in pitch will result in sub-optimal performance. The data collected during the initial diving and then that surfacing at the end of the mission are excluded because there will be large changes in pitch during these stages of the mission that will pollute the identification of pitch error.

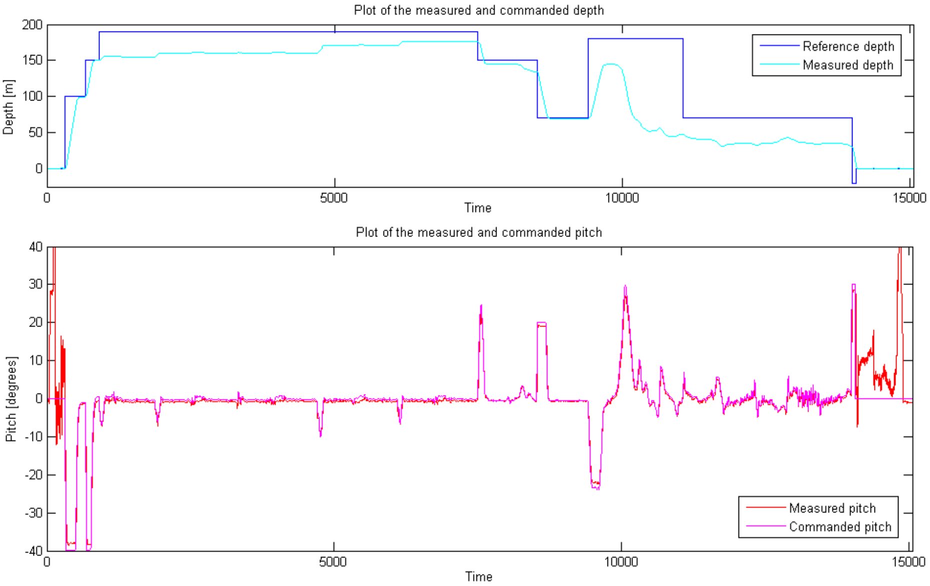


Figure 5.5: Plots showing the measured depth and reference depth relative to the measured pitch and commanded pitch

### The comparison approach

The comparison approach exploits the measured and commanded pitch data to check for a pitch error. A difference between measured pitch and commanded pitch indicates that the AUV is not completely able to follow the commanded pitch (see Figure 5.6). It is assumed that the difference in measured pitch and commanded pitch is caused by a misalignment of the weight along the x-axis. It should, however, be noted that some of the deviation might be caused by measurement noise and bias. If the controller calculating the thrust and rudder angle assumes that the weight is evenly distributed, but it is not, the calculated pitch will not be able to give the AUV the right pitch angle.

By comparing measured and commanded pitch, a possible pitch error can be detected. By subtracting the value of the commanded pitch from the measured pitch for each time step, the average of the resulting values will give an indication of a pitch error. This approach was implemented with the algorithm shown in Appendix D.2.

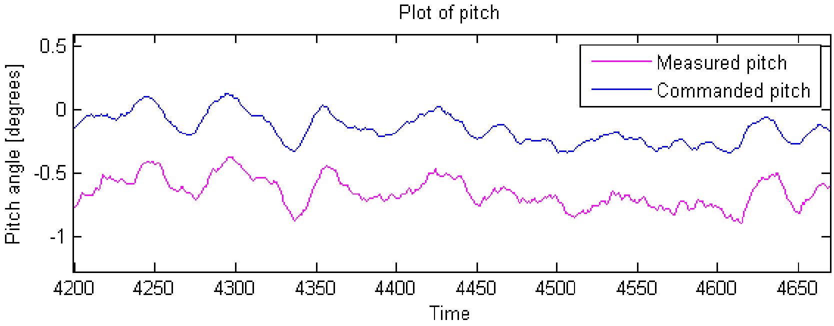


Figure 5.6: Plot of measured and commanded pitch, zoomed in

By viewing the plot in Figure 5.7, it can be seen that the commanded pitch is about zero degrees, while the measured pitch is slightly negative. The algorithm in Appendix D.2, which has been derived to detect such errors, will yield a negative value for the data presented in Figure 5.6. A negative value indicates that the nose of the AUV tilts downwards, while a positive value indicates that the nose tilt upwards.

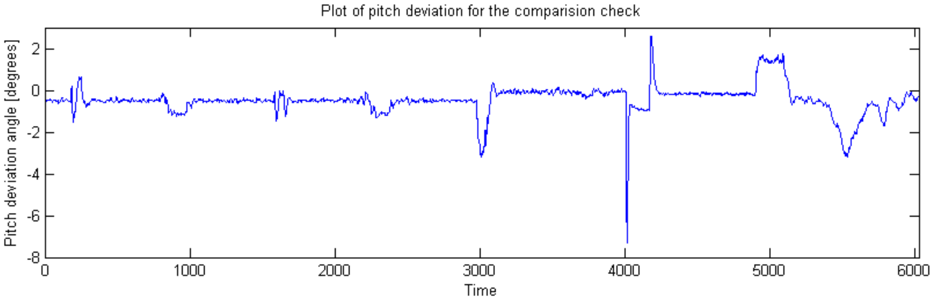


Figure 5.7: Plot of the deviation in pitch from the comparison check

### The depth check approach

A deviation in pitch can also be checked by looking at the measured pitch when the depth is stable, meaning when the depth does not change from one sample to the next. When the measured depth is stable, the pitch should be zero. This approach was implemented with the algorithm shown in Appendix D.3.

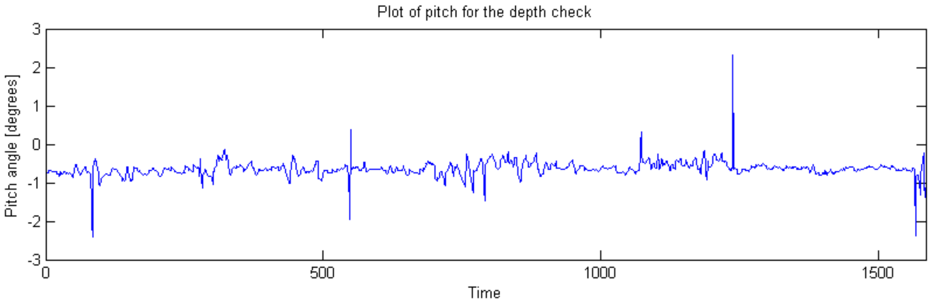


Figure 5.8: Plot of the pitch from the depth check

By viewing the plot in Figure 5.8, it can be seen that the pitch is slightly negative with some positive spikes. The code in Appendix D.3 will yield a negative value, slightly smaller than the result of the comparison check.

## 5.3.3 Checking for errors in roll

Roll is the rotation about the x-axis (see Section 2.1 and Figure 2.3). This rotation is affected by the weight distribution along the y-axis. If there is more weight on the starboard side of the AUV, it will get a positive roll angle. If there is more weight on the port side, it will get a negative roll angle. A roll error will spoil many of the measurements that the vehicle performs with sensors mounted on the underside of the hull to ”look” straight down at the seafloor. The valid deviation in pitch is ± 0.1 degrees.

The roll angle is measured during missions. In contrast to the pitch, no reference or commanded value for the roll is known. The roll is not controlled actively, it is stabilized by the precise distribution of weight inside the AUV. The AUV is loaded a little heavier on the port so that it has a small positive roll angle. This is to counteract the torque from the propeller that rotates clockwise, which pushes the water backwards causing a forward thrust. The normal operation forward linear velocity is 2 m/s at which the propeller speed is 160 rpm, and then the roll will be zero due to rotational torque of the propeller. Figure 5.9 shows the propeller speed, the forward linear velocity and the roll angle.

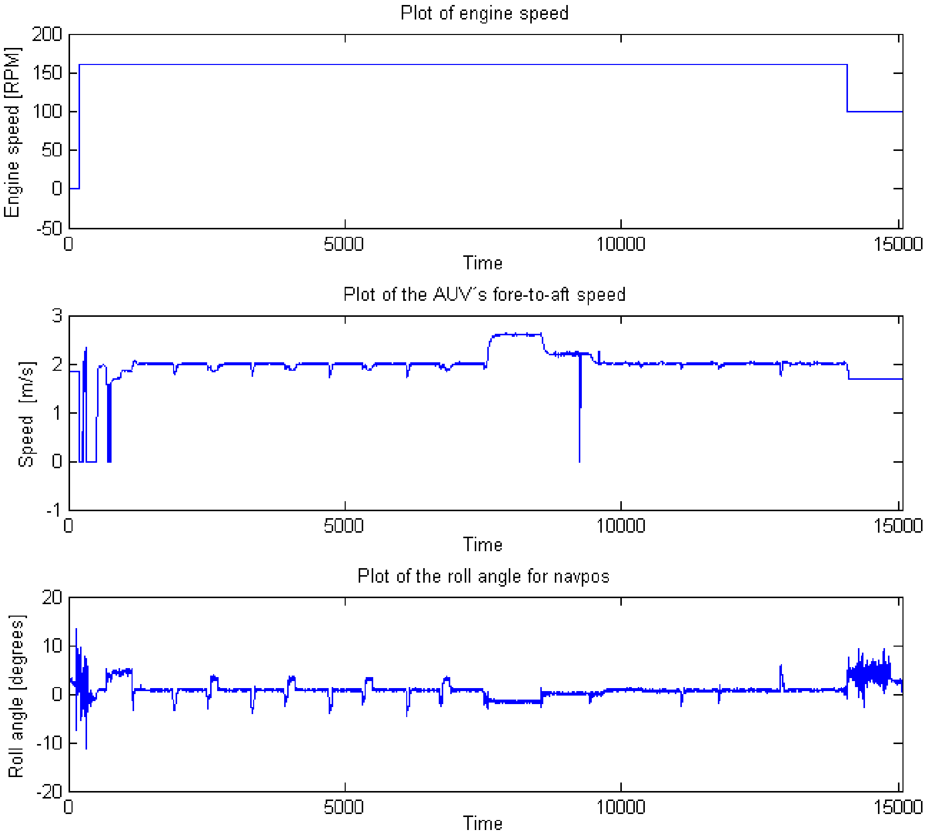


Figure 5.9: Plot of the propeller speed, the velocity and the roll angle

During missions when the AUV has forward movement, the desired roll angle is zero. To check if the AUV is correctly ballasted along the y-axis and then has the correct roll angle, the measured roll angles are checked at samples where the propeller speed is 160 rpm and forward velocity is 2 m/s. At these samples the roll angle should be zero. If not, there is a ballast error along the y-axis. This approach was implemented with the algorithm shown in Appendix D.4.

In Figure 5.10 it can be seen that the roll is slightly positive with both positive and negative spikes. The code in Appendix D.4 will yield a positive roll error value based on the data presented in Figure 5.9.

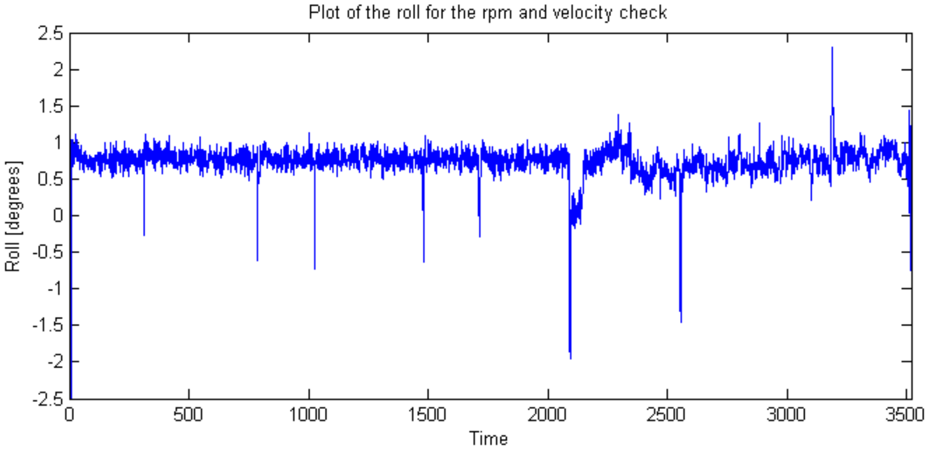


Figure 5.10: Plot of the roll angle for the roll check

## 5.4 Determining the required ballast adjustment

Kongsberg Maritime want their AUV to be in a state of stable equilibrium with neutral buoyancy (see Section 2.6), which requires two conditions to be fulfilled:

1. The weight and the buoyancy force must be equal.
2. The CG and CB must coincide along the x- and y-axis, while they are some distance apart along the z-axis.

However, the AUV is not by default initially in a state of stable equilibrium with neutral buoyancy. Therefore, after identifying the ballast errors, a process that determines the required ballast adjustments is needed so that the AUV gains stable equilibrium with neutral buoyancy. According to the specifications given by Kongsberg Maritime, the buoyancy force and the CB are fixed and cannot be changed. The ballast of the AUV can only be adjusted by changing the weight and the CG. The ballast adjustments should make the AUV satisfy the two conditions mentioned above.

The CG can be moved by adding different weights at the four different point of adjustment (see Section 3.1). Adding more weight in the fore will move the CG forward and vice-versa. Adding more weight at the starboard side will move the CG towards the starboard side and vice-versa. The optimal ballast adjustment will put the CG as close as possible to the CB along the x- and y-axis while the weight should equalize the buoyancy force. When determining the required ballast adjustment, a tradeoff between the two conditions for stable equilibrium with neutral buoyancy has to be made. Because of the weight available for adjustment, it might not be possible to completely fulfil both conditions. Which of the two conditions is prioritized will have a profound impact on the system.

If the weight is larger than the buoyancy force, the AUV will be negatively buoyant and therefore sink if no thrust is applied upwards. The AUV will have to use extra thrust to keep it from sinking, and if not counteracted, the AUV might accidentally hit the seafloor when it is supposed to move just above it. On the other hand, if the weight is smaller than the buoyancy force, the AUV will be positively buoyant and float up. In this case too, the AUV will have to use extra thrust to keep it at the desired depth in the water. Thus, the weight/buoyancy balance of the AUV is important. Nevertheless, the correct orientation is also important. If the AUV has a negative pitch angle it might dive into the sea floor when it close to it. In addition, if the AUV has a positive or negative roll angle, that might affect its turning.

It has been decided, in agreement with Kongsberg Maritime, that the priority for the ballast adjustment will be:

1. The weight/buoyancy balance
    (a) Avoid negative buoyancy
    (b) Avoid positive buoyancy
2. The orientation
    (a) Correct pitch angle, the CG and the CB coincide along the x-axis
    (b) Correct roll angle, the CG and the CB coincide along the y-axis
3. The stability
    (a) The CG located under the CB
    (b) Some distance between the CG and the CB along the z-axis

The weight/buoyancy balance is the top priority as this will affect the AUV's power consumption during the entire mission. In addition, if the vehicle is too heavy, it might accidentally dump into the seabed when operating close to it and get damaged. The next priority is the orientation, which affects the AUV's controllability and accuracy during its mission. Correct pitch angle is prioritized over the correct roll angle because an incorrect pitch angle has bigger consequences than an incorrect roll angle. Incorrect pitch may result in the AUV diving into the seafloor. Moreover, it will cause increased drag on the vehicle because the vehicle shows more of its sides at the direction of motion and becomes less streamlined. The power consumption will therefore increase. An incorrect roll, on the other hand, might result in suboptimal turning. However, the most important issue concerning incorrect roll, is that Kongsberg Maritime's AUVs have sensors that search the seabed. These sensors are mounted on the underside of the AUV and points downwards at the seabed. If the AUV has a roll angle that is not zero, the sensor will not point directly down on the seabed, which it is supposed to do.

The deviation limits are as follows:

- for the weight/buoyancy imbalance it is +1.2 kg, which is the smallest available weight that is possible to add to the AUV (see Section 3.1), and -0.0 kg because the AUV should not be negatively buoyant
- for the deviation in commanded and measured depth it is +0.1 m and -0.0 m, which ensures that the AUV is not negatively buoyant (see Section 5.3.1)
- for the pitch angle it is ± 0.5 degrees (see Section 5.3.2)
- for the roll angle it is ± 0.1 degrees (see Section 5.3.3)

The stability is not prioritized in the system design. This is not because the stability is not important, but because the system will not be able to do much about it. Initially the AUV's payloads should be configured, by Kongsberg Maritime's operator, so that the CG is located underneath the CB. This is done by putting the heaviest payloads at the button and the lighter payloads at the top. The locations of the CG and the CB along the z-axis have to prearranged, the system will not be able to change the CB and can only slightly change the CG. The CG can only be slightly moved along the z-axis because the four points of adjustment is located at the middle of the z-axis, so adding weights will only move the CG slightly upwards.

In the following sections, two approaches for determining the ballast adjustment are presented. The CG shifting approach, presented in Section 5.4.1, is the method used in first mission mode. While the "slow control loop" approach, presented in Section 5.4.2, is the method that is used in the pre mission mode. These approaches calculates accurate ballast adjustments. However, it is not necessarily possible to achieve these precise adjustments with the adjustment weights that are available (see Section 3.1). The calculated adjustments will therefore have to processed to match available weights. How this is done will be explained in Section 5.5.4.

### 5.4.1 CG shifting with weight measurements

In the first mission mode, the calculation of the required ballast adjustment is based on an approach where the CG of the vehicle will be shifted. The current CG can be calculated with the initial weight measurements from the weighing method (see Section 4.2). Hence, the ballast adjustment can be done by determining the weight adjustment needed to shift the CG so that it lays directly under the CB. By adding different weights to the four points of adjustment (see Section 3.1), the CG can be moved to coincide with the CB along the x- and y-axis. When the CG and the CB satisfy this requirement, and the total weight and buoyancy force is equal, the AUV is in a state of stable equilibrium with neutral buoyancy (see Section 2.6).

According to the specifications in Table 3.1, the AUV is "underweight" since the weight in water is negative. That the weight in water is negative means that the buoyancy force is larger than the weight. Weight should therefore be added to the AUV so that the total weight and buoyancy force becomes equal. The required mass, $m_{dif}$, is easily found by using Equations 5.1 and 5.2. If $m_{dif} = 0$ and the CG and the CB satisfies the conditions of stable equilibrium, there are no ballast errors. However, if $m_{dif} \neq 0$, then the AUV has a ballast error according the requirements in Section 2.7.1.

With $m_{dif}$ known, the next step will be to calculate how the required weight should be distributed between the four points of adjustments. This weight distribution is based on the relationships between the CG and the CB. To fulfil the requirement for stable equilibrium, the CB and the CG should coincide along the x- and y-axis, such that:

$$\begin{bmatrix} x_{CB} \\ y_{CB} \end{bmatrix} = \begin{bmatrix} x_{CG} \\ y_{CG} \end{bmatrix} \tag{5.3}$$

Where $[x_{CB}\ y_{CB}]$ is the known CB, which is provided by Kongsberg Maritime, and $[x_{CG}\ y_{CG}]$ is the calculated CG based on the weighting method in Section 4.2.

However, it is not given that Equation 5.3 is satisfied. When the AUV has a ballast error in its orientation, the CG and the CB will not coincide along the x- and y-axis.

The different alternatives for the relationships between the CG and the CB, and how the weight then will be distributed, are listed below:

1. When the CG and the CB already coincide. Then the weight will be divided between the four points of adjustment such that their weight moments are equal.
2. The CG is shifted along the x-axis compared to the CB, while they already coincides along the y-axis, which gives a pitch error. Then the weight will be divided accordingly between the two points of adjustment in the fore and the two in the aft. The pairs will divide the weight equally between them.
3. The CG is shifted along the y-axis compared to the CB, while they already coincides along the x-axis, which gives a roll error. Then the weight will be divided accordingly between the two adjustable weights on the starboard and the two on the port side. The pairs will divide the weight equally between them.
4. The CG is shifted along the x- and the y-axis compared to the CB, which gives a pitch and roll errors. Then the weight will be divided accordingly between all the points of adjustment.

The aim of the ballast adjustment is to shift the CG so that it coincides with the CB along the x- and y-axis. The required adjustment will be based on a calculated shift in CG. The CG shift will move the overall CG of the AUV towards the CB. This CG shift can be expressed as the difference between the CG and the CB along the x- and y-axis:

$$\begin{bmatrix} x_{CG} \\ y_{CG} \end{bmatrix}_{shift} = \begin{bmatrix} x_{CB} \\ y_{CB} \end{bmatrix}_{known} - \begin{bmatrix} x_{CG} \\ y_{CG} \end{bmatrix}_{calculated} \tag{5.4}$$

The calculated CG and the CG shift can be derived with the theory in Section 2.4 when assuming that the AUV is a system of eight particles. These eight particles, which each have a mass $m_i$, include:

- the four points of weight measuring (see Section 4.2), $P_i$ for $i = 1, 2, 3$ and 4, that are located at the coordinates $r_i$ for $i = 1, 2, 3$ and 4

- the four points of adjustment (see Section 3.1), $P_i$ for $i = 5, 6, 7$ and 8, that are located at the coordinates $r_i$ for $i = 5, 6, 7$ and 8

The current CG is calculated based on the measurements from the weighing (see Section 4.2):

$$\begin{bmatrix} x_{CG} \\ y_{CG} \end{bmatrix}_{calculated} = \frac{1}{M_{AUV}} (\sum_{i=1}^{4} m_i r_i) \tag{5.5}$$

The CG shifting will be achieved by adjusting the weight at the four points of adjustment. The CG shift can be expressed as the CG of this weight adjustment:

$$\begin{bmatrix} x_{CB} \\ y_{CB} \end{bmatrix}_{shift} = \frac{1}{m_{dif}} (\sum_{i=5}^{8} m_i r_i) \tag{5.6}$$

The resulting CG shift from Equation 5.4 with will Equation 5.6 determines how to distribute the required weight, $m_{dif}$. The resulting expression for the weight distribution becomes:

$$\frac{1}{m_{dif}} (\sum_{i=5}^{8} m_i r_i) = \begin{bmatrix} x_{CB} \\ y_{CB} \end{bmatrix}_{known} - \frac{1}{M_{AUV}} (\sum_{i=1}^{4} m_i r_i) \tag{5.7}$$

Where the $r_i$ for i = 1 to 8 are known, as are the $m_i$ for i = 1 to 4, while the $m_i$ for i = 5 to 8 are the unknown ballast adjustments.

By expanding Equation 5.7, two equations can be derived for the two axes that are considered, the x- and the y-axis:

$$\frac{1}{m_{dif}} (\sum_{i=5}^{8} m_i x_i) = x_{CB} - \frac{1}{M_{AUV}} (\sum_{i=1}^{4} m_i x_i) \tag{5.8}$$

$$\frac{1}{m_{dif}} (\sum_{i=5}^{8} m_i y_i) = y_{CB} - \frac{1}{M_{AUV}} (\sum_{i=1}^{4} m_i y_i) \tag{5.9}$$

The only unknown variables are $m_5$, $m_6$, $m_7$ and $m_8$, which represent the weight adjustment. These variables have to be positive and are constrained by the mass that has to be added, such that:

$$m_5 + m_6 + m_7 + m_8 = m_{dif} \tag{5.10}$$

Additional constraints are set according to prerequisite knowledge in the various relationships between the CG and the CB. For alternative 2, in the list of relationships between the CG and the CB, where the weight is distributed equally between the starboard and port side, the adjustment masses are constrained to ensure that the weight is not shifted along the y-axis. To ensure this, the moment about the y-axis caused by the added mass will be restricted. The moments are the product of the applied force of the added mass and the distance from the CO where it is added, and can be expressed as $\tau = Fr = mgr$. In the case of alternative 2, the moments will be constrained by $\tau_5 = \tau_6$ and $\tau_7 = \tau_8$. However, as most AUVs are symmetric around the y-axis, and the adjustment points on the starboard and port side are located symmetrically, the arms of the moment will be equal. The constraints can therefore be reduced to:

$$m_5 = m_6 \quad \text{and} \quad m_7 = m_8 \tag{5.11}$$

For alternative 3, where the weight is distributed equally between the fore and aft, the adjustment masses can be constrained by $\tau_5 = \tau_7$ and $\tau_6 = \tau_8$, which will ensure that the weight is not shifted along the x-axis. In this case there might not be symmetry in the moment arms. Equation 5.12 with the moment arms, $x_i$ for i = 5, 6, 7 and 8, will be used to ensure that the arms of the added weights are taken into consideration when distributing the weight, $m_{dif}$.

$$m_5 x_5 = m_7 x_7 \quad \text{and} \quad m_6 x_6 = m_8 x_8 \tag{5.12}$$

The different alternatives of the list of the relationships between the CG and the CB, demands different sets of equations. If alternative 2 is matched, where there is a misalignment along the x-axis, the weight distribution will be calculated with Equations 5.8, 5.10 and 5.11:

$$\frac{1}{m_{dif}} \sum_{i=5}^{8} m_i x_i = x_{CB} - \frac{1}{M_{AUV}} \sum_{i=1}^{4} m_i x_i$$

$$\begin{aligned} m_{dif} &= m_5 + m_6 + m_7 + m_8 \\ m_5 &= m_6 \\ m_7 &= m_8 \end{aligned}$$

If alternative 3 is matched, where there is a misalignment along the y-axis, the weight distribution will be calculated with Equations 5.9, 5.10 and 5.12:

$$\frac{1}{m_{dif}}\sum_{i=5}^{8} m_i y_i = y_{CB} - \frac{1}{M_{AUV}}\sum_{i=1}^{4} m_i y_i$$

$$m_{dif} = m_5 + m_6 + m_7 + m_8$$

$$m_5 x_5 = m_7 x_7$$

$$m_6 x_6 = m_8 x_8$$

Alternative 1 is a special situation where the distribution of the weight can be calculated by setting the $CG_{shift} = \begin{bmatrix} 0 & 0 \end{bmatrix}$ in Equation 5.6, which gives:

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{1}{m_{dif}}(m_5 x_5 + m_6 x_6 + m_7 x_7 + m_8 x_8) \\ \frac{1}{m_{dif}}(m_5 y_5 + m_6 y_6 + m_7 y_7 + m_8 y_8) \end{bmatrix} \tag{5.13}$$

By assuming symmetry around the y-axis, Equation 5.13 becomes:

$$\begin{bmatrix} (m_5 + m_6)x_5 \\ m_5 + m_7 \end{bmatrix} = \begin{bmatrix} -(m_7 + m_8)x_7 \\ m_6 + m_8 \end{bmatrix} \tag{5.14}$$

With Equations 5.10, 5.11 and 5.12, the mass distribution in Equation 5.14 becomes:

$$m_5 + m_6 = m_{dif}\frac{x_7}{x_7 - x_5} \tag{5.15}$$

$$m_7 + m_8 = m_{dif}\frac{x_5}{x_5 - x_7} \tag{5.16}$$

Where the weight adjustment in the fore will have $m_5 = m_6$ and the weight adjustment in the aft will have $m_7 = m_8$. In addition, they will have to comply with Equation 5.10.

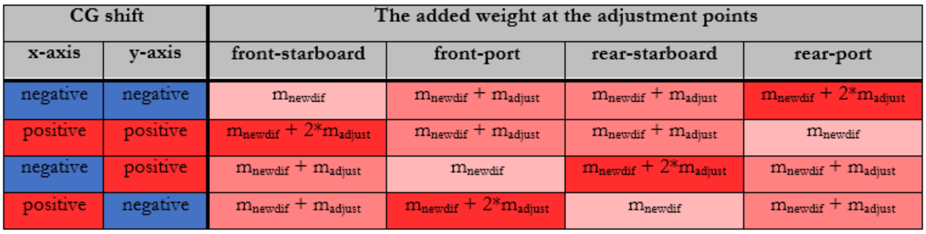
If alternative 4 is matched, where there are misalignments along both the x- and y-axis, and then there will not be enough equations to find a suitable weight distribution. Thus, a slightly different method will be used in this case. To determine the weight distribution, the CG shift will be calculated using Equation 5.4. According to [14], the CG will move in the same direction as any added weight. Therefore, if the calculated CG shift is:

- along the x-axis:
  - positive: more of the weight should be added in the fore
  - negative: more of the weight should be added in the aft
- along the y-axis:
  - positive: more of the weight should be added in the starboard side
  - negative: more of the weight should be added in the port side

Figure 5.11 shows how the ballast adjustments is determined based on the calculated CG shift in Equation 5.4. This adjustment might not be optimal, however, it will improve the ballasting of the vehicle. The required weight, $m_{dif}$, will be distributed according to the table in Figure 5.11, where the $m_{newdif}$ is:

$$m_{newdif} = m_{dif} - 4m_{adjust} \tag{5.17}$$

Where the differing weight adjustment, $m_{adjust}$, is the wanted difference in the weight adjustment at the four points of adjustment. The new weight adjustment, $m_{newdif}$, is added at each point. In addition, the four units of the differing weight adjustment, $m_{adjust}$, is added to some of the points to shift the CG in a certain direction.



| CG shift | | The added weight at the adjustment points | | | |
|---|---|---|---|---|---|
| x-axis | y-axis | front-starboard | front-port | rear-starboard | rear-port |
| negative | negative | $m_{newdif}$ | $m_{newdif} + m_{adjust}$ | $m_{newdif} + m_{adjust}$ | $m_{newdif} + 2*m_{adjust}$ |
| positive | positive | $m_{newdif} + 2*m_{adjust}$ | $m_{newdif} + m_{adjust}$ | $m_{newdif} + m_{adjust}$ | $m_{newdif}$ |
| negative | positive | $m_{newdif} + m_{adjust}$ | $m_{newdif}$ | $m_{newdif} + 2*m_{adjust}$ | $m_{newdif} + m_{adjust}$ |
| positive | negative | $m_{newdif} + m_{adjust}$ | $m_{newdif} + 2*m_{adjust}$ | $m_{newdif}$ | $m_{newdif} + m_{adjust}$ |

Figure 5.11: Mapping of weight adjustment based on CG shifting

The calculations presented for all the relationships between the CG and the CB, form the CG shifting approach. The CG shifting approach aims to shift the CG towards the CB so that the CG end up coinciding with the CB along the x- and y-axis. However, there is a limit to how much the CG can be shifted since the adjustment can only be done be adding additional weights. The balance between total weight and the buoyancy force on the AUV has to be taken into account when adding additional weights. Too much additional weight will make the AUV negatively buoyant.

### 5.4.2 ”Slow control loop” with mission data

Before the pre mission mode is ran, the AUV has been on a mission and collected data that has be processed in the post mission mode (see Sections 5.3 and 3.2). These data indicate how the AUV behaves in the water with the added weights. The previous weight adjustment done in the first mission mode might not have been optimal, and the collected data can then give an indication of current ballast errors. As discussed in Section 5.4, the AUV will experience a ballast error if the two conditions for stable equilibrium with neutral buoyancy are not satisfied (see Section 2.6). To determine if the AUV's ballast is correct, the weight, buoyancy, CG and CB is checked in the post mission mode (see Section 5.3). However, none of the mission data collected during the mission can give a direct value for the mass distribution, and in that extension the CG. Only an indication of the how the mass is distributed can be found by observing the pitch and roll angles of the AUV (see Section 5.3.2 and 5.3.3). Unfortunately, there is no direct mathematical or physical relationship between the angles and the size of the mass distribution, which is essentially the CG. This means that the CG is unknown.

With the CG unknown, the method for determining the ballast adjustment in the pre mission mode will have to be based on the AUV's pitch and roll angles. The pitch and roll errors are used to give an indication of the weight distribution, and therefore also indirectly the CG. Any errors in pitch and roll indicate that the weight is improperly distributed, meaning that the CG does not coincide with the CB along the x- and y-axis. The pitch and roll errors can therefore be used to determine the required ballast adjustment. An ad hoc method has been designed for determining the ballast adjustment. This ad hoc method is designed for this specific problem; its goal is to find an optimal combination of added weights to ensure the AUV is in a stable state of equilibrium with neutral buoyancy by minimizing the pitch and roll errors as well as the weight/buoyancy imbalance.

An initial adjustment will be carried out in first mission mode before the first mission, in accordance with the weighting method in Section 4.2. The AUV will then collect data on the water properties, depth, pitch and roll angles during its first mission. With these data, which are processed in the post mission mode, the pre mission mode will calculate new adjustments that aim to make the ballast of AUV more optimal. Then, the AUV will go on another mission with the new adjustments, and it will collect new data. Then the process starts over. This process will be a type of control loop. Each time the pre mission mode is ran is an iteration of the control loop. It will, therefore, be a very slow control loop where each time step is either the time of a whole mission or the time between post mission procedures and pre mission procedures where a human operator does any needed adjustments (see Figure 5.12). Because of the human interactions, this system is a human-in-the-loop system. Human-in-the-loop is a term used to describe a model or system that requires human interaction during runtime [17].

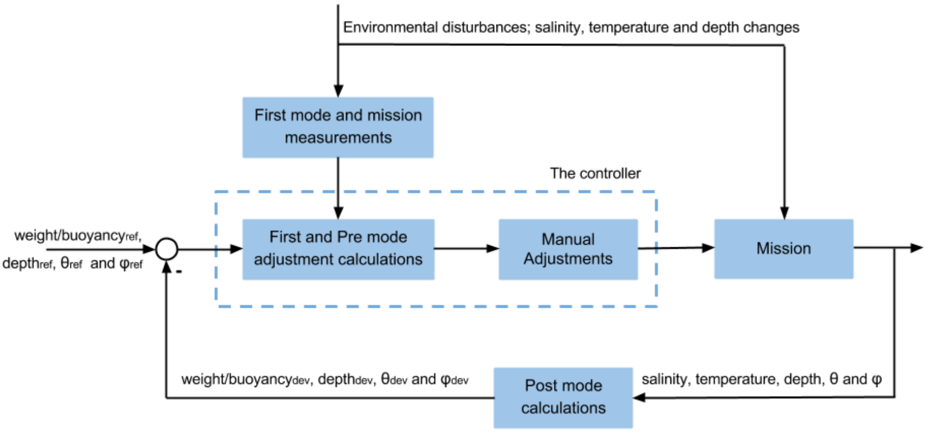


Figure 5.12: The slow control loop for ballast adjustment based on changes in weight/buoyancy, depth, pitch and roll deviation

The human interaction will affect the performance of the system. In parts of the system, the progress depends on some inputs from an operator. If these inputs are faulty, the system's outputs will be affected and in the worst case the system may fail because of the errors made by the operator. In order to prevent operator errors, the user interactions are kept to a minimum and when user interactions are needed, the operator's tasks are explained with clear instructions to avoid misunderstandings and errors in inputs. The system aims to be user friendly, and easy and quick to learn[1].

The control loop in Figure 5.12 is a closed feedback loop with feedforward of environmental disturbances[2]. In this case, the reference signal is the desired weight/buoyancy balance, depth, pitch and roll, which all are zero. The weight/buoyancy balance, and the depth, pitch and roll deviations are calculated in the post mission mode based on sensor measurements done by the AUV during

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[1] For more information on user interface design see *Designing the User Interface* by Shneiderman, B. and Plaisant C., publisher Pearson, 2011, 5th edition

[2] For more information on control theory see *Reguleringsteknikk* by Balchen, J.G., Andresen, T. and Foss, B.A., published in Trondheim by the Department of Engineering Cybernetics, Norwegian University of Science and Technology, 2003, 5th edition (Norwegian)

missions (see Section 5.3). The deviation measurements are subtracted from the desired values, making an error signal for the controller. The error signal will be:

$$e_d(k) = d_{ref} - d_{meas}(k) \tag{5.18}$$

$$e_b(k) = W - b_{meas}(k) \tag{5.19}$$

$$e_p(k) = p_{ref} - p_{meas}(k) \tag{5.20}$$

$$e_r(k) = r_{ref} - r_{meas}(k) \tag{5.21}$$

Where the $e_d(k)$, $e_b(k)$, $e_p(k)$ and $e_r(k)$ are the current errors in depth, weight/ buoyancy balance, pitch and roll, respectively, the $d_{ref}$, $W$, $p_{ref}$ and $r_{ref}$ are the reference values that act as set points, and the $d_{meas}(k)$, $b_{meas}(k)$, $p_{meas}(k)$ and $r_{meas}(k)$ are the current, measured depth, buoyancy, pitch and roll deviations.

The error signals are used along with the measurements from the first mission mode and the mission data to determine a new ballast adjustment. The environmental disturbances are the water temperature, salinity and the operational depth. Any changes in these parameters need to be adjusted for.

The controller is two parted:

1. The first part is the software tool that calculates the required adjustments
2. The second part is a human operator who manually adjusts the ballast based on the required adjustments calculated in the previous part

With the new ballast adjustment the AUV goes on a new mission during which sensors in the AUV collects new mission data. The salinity, temperature, depth, pitch angle and roll angles collected are used as the system's outputs and are handled in the post mission mode. The resulting errors identified by the post mission mode are used in the pre mission mode to determine a new ballast adjustment that will improve the ballasting of the AUV.

The first step when determining a new ballast adjustment is to check the current weight against the buoyancy force. This is done by using the depth comparing approach presented in Section 5.3.1. This check yields three different outcomes:

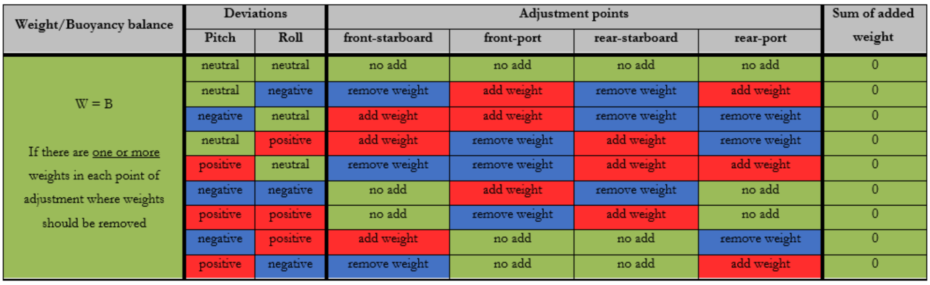
- If the commanded and measured depth are equal within a valid deviation, the new ballast adjustment will attempt not to change the overall weight of the vehicle, it will only change the weight distribution.
- If the commanded depth is greater than the measured depth, the new ballast adjustment will make sure to add some weight to the overall weight in addition to changing the weight distribution.

- If the commanded depth is smaller than the measured depth, the new ballast adjustment will make sure to remove some weight to the overall weight in addition to changing the weight distribution.

The second step will be to determine how to minimize the pitch and roll errors. Depending on the sign of the pitch and roll errors, $e_p(k)$ and $e_r(k)$, weights will be added or removed on the AUV, in accordance with the four available points of adjustment. The weight distribution is changed little by little, in each iteration of the ”slow control loop”, by adding or removing weights. How much weight should be added or removed depends on the relationship between the weight and the buoyancy force, which is calculated with Equation 5.2 as explained in the weight/buoyancy comparing approach (see Section 5.3.1):

1. When the weight and the buoyancy force are equal: the smallest available weights are used in a configuration that will add up to zero added or removed weight in total (see Figure 5.13)
2. When the weight is smaller than the buoyancy force: the size of the weights used depends on the ”missing” weight, $m_{dif}$
3. When the weight is greater than the buoyancy force: the size of the weights used depends on the ”excess” weight, $m_{dif}$

Figure 5.13 shows how the ballast adjustments are determined based on the deviations in pitch and roll for the situation where there are no depth error or weight/buoyancy imbalance. The result of the ballast adjustments done is not acquired before the AUV has been on new mission, and its mission data are processed in the post mission. If the errors in pitch and roll become smaller, then the adjustment is repeated. This is done repeatedly until the errors in pitch and roll are as small as possible.



| Weight/Buoyancy balance | Deviations | | Adjustment points | | | | Sum of added weight |
|---|---|---|---|---|---|---|---|
| | Pitch | Roll | front-starboard | front-port | rear-starboard | rear-port | |
| W = B<br>If there are one or more weights in each point of adjustment where weights should be removed | neutral | neutral | no add | no add | no add | no add | 0 |
| | neutral | negative | remove weight | add weight | remove weight | add weight | 0 |
| | negative | neutral | add weight | add weight | remove weight | remove weight | 0 |
| | neutral | positive | add weight | remove weight | add weight | remove weight | 0 |
| | positive | neutral | remove weight | remove weight | add weight | add weight | 0 |
| | negative | negative | no add | add weight | remove weight | no add | 0 |
| | positive | positive | no add | remove weight | add weight | no add | 0 |
| | negative | positive | add weight | no add | no add | remove weight | 0 |
| | positive | negative | remove weight | no add | no add | add weight | 0 |

Figure 5.13: Mapping of weight adjustment based on pitch and roll when the weight/buoyancy balance is W = B

The problem when adjusting the ballast of an AUV is that it might not be possible to remove any weight. If no weight previously has been added in a point of adjustment, it will not be possible to remove any weight in this point later. It is only possible to remove weights that have already been added. In the cases where there are no weights in one or more of the four points of adjustment, tradeoffs between the two conditions for a state of stable equilibrium with neutral buoyancy have been done. Figures E.1 and E.2 show the full table for ballast adjustment with all the different cases, and the implemented code of table can be seen in Appendix E.2.

One of the main concerns, when adjusting the ballast, is that the weight should not be significantly larger than the buoyancy force. The reason for this; if the AUV is heavier than its natural buoyancy in a case of emergency where the AUV loses power, the AUV will sink. The weight/buoyancy balance is prioritized over adjusting the pitch and roll since the pitch and roll are must significant when the AUV is in motion and therefore have power. However, to be able to get acceptable pitch and roll angles, their adjustment have to be prioritized over the weight/buoyancy balance in cases where it is assumed safe to change the weight/buoyancy balance a little. One of these situations can be when the weight/buoyancy is neutral, then it is acceptable that the AUV becomes slightly positively buoyant in order to adjusted the pitch and roll.

A check for best adjustment is indirectly implemented in the adjustment table (see Figures E.1 and E.2). If there is no deviation in the weight/buoyancy balance, no weight will be added or removed. If there is no deviation in pitch, no adjustment will be made for the pitch, and similarly for roll. In short, if one of the conditions for neutral buoyancy and a state of stable equilibrium are satisfied, then the system will endeavor to not undo this part of the adjustment. Therefore, if both neutral buoyancy and a state of stable equilibrium are satisfied, the system will not ask for any adjustments. All adjustments and their resulting errors are stored in the ballasting file (see Section 5.5.2).

## 5.5 Other system features

The main tasks of the system is to identify ballast errors and determine suitable adjustments. This is done with three different mission modes. These modes are ran in a specific sequence and they depend on each other's stored information (see Section 5.2). To ensure the correct behavior, several additional features have been implemented into the system. These features include specially implemented sections that perform a specific task, like the start-up sequence, the temperature checking and the mapping the calculated adjustment to the available weights. In addition, attributes that organizes the use of the system are presented, this includes the configuration ID number and the ballasting file.

### 5.5.1 The configuration ID number and system start-up

The configuration ID number was introduced to keep track of the various AUVs. This number will be used in the start-up of the system and when one of the mission modes store data in a specially designed ballasting file (see Section 5.5.2). The configuration ID number is an xx-xx-xx code. This ID identifies a specific AUV with a formation of payloads in a certain water of operation.

The system will start up by asking the user for the configuration ID number. The system checks its folders for this number. If it exists, the configuration ID number belongs to a known and earlier used configuration of an AUV. The system then asks the user whether to run the pre or post mission mode. If the configuration ID number does not exist, a new configuration is indicated and the system will then run the first mission mode.

### 5.5.2 The ballasting file

Each AUV with a unique configuration ID number has its own ballasting file. This file will be:

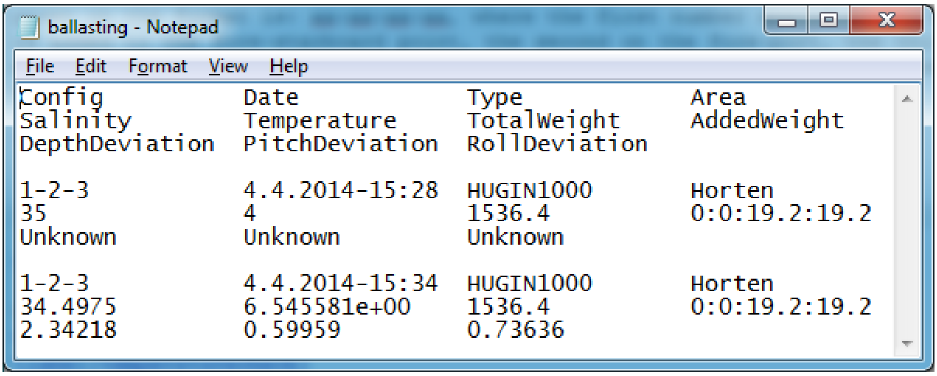
- created by the first mission mode with the configuration ID number
- updated with the processed data in the post mission mode
- used for ballast check and to determine suitable ballast adjustments in pre mission mode, and then updated

When the ballasting file is created in the first mission mode, it will be filled with the date and time, configuration ID number, type of AUV, area of operation, temperature, assumed salinity, the total weight of the AUV and the added weight. The post mission will update the ballasting file with processed mission data and the identified errors. These data will be loaded and used in the pre mission mode for determining new and improved ballast adjustments.

The ballasting file will be located inside a folder of the accordingly configuration ID number and is named ”ballasting”. It is a standard txt-file with a specified format, and contains the following data:

- configuration ID number
- date of last uploaded data
- type of AUV
- area of operation
- salinity and temperature
- total weight and added weight
- depth, pitch and roll errors

Figure 5.14 shows an example of a ballasting file, which was made by using the implemented system. The file has been used twice, this we know since there are only two rows of data. The first row of values was created in first mission mode when the depth, pitch and roll errors were unknown, which is why those columns are filled with ”Unknown”. The second row was added by the post mission mode and contains updated data including the identified depth, pitch and roll error.



```
Config          Date            Type            Area
Salinity        Temperature     TotalWeight     AddedWeight
DepthDeviation  PitchDeviation  RollDeviation

1-2-3           4.4.2014-15:28  HUGIN1000       Horten
35              4               1536.4          0:0:19.2:19.2
Unknown         Unknown         Unknown

1-2-3           4.4.2014-15:34  HUGIN1000       Horten
34.4975         6.545581e+00    1536.4          0:0:19.2:19.2
2.34218         0.59959         0.73636
```

Figure 5.14: Ballasting file example

The added weight is given on the format: xx:xx:xx:xx, where the first number specified how much weight is added to the fore-starboard point, the second on the fore-port, the third on the aft-starboard and the fourth on the aft-port. The date is given on the format: dd.mm.yyyy-hh:mm.

### 5.5.3 Temperature check

The temperature of the water is an important measurement in the calculation of the current buoyancy force. It is therefore important that the temperature is updated based on mission data. The temperature is measured by the AUV during missions, however, the temperature of the water will change with time, weather and ocean currents. The date of the last measured temperature will therefore be checked to decide whether the temperature in the mission data can be used or not. If too long a period has passed since the last mission the temperature measured then might not be accurate anymore and a new temperature should be entered. This temperature can be manually measured or estimated.

The approved period between missions, in which the temperature from the previous mission can be reused, is set to one month. However, the operator has the option of changing the temperature if it was gone less time too. The operator will be presented with the previous measured temperature, and is asked if this temperature should be used in the calculation of the ballast adjustments for the next mission. If the operator does not want to reuse it, the operator can enter a new temperature. The algorithm used for date checking and temperature setting is shown in Appendix B.

### 5.5.4 Mapping the ballast adjustment

The required ballast adjustments are accurately calculated with the approaches presented in Sections 5.4.1 and 5.4.2. However, the actual possible ballast adjustments of the AUV are constrained by the available adjustment weights, $W_{1,2kg}$, $W_{2,4kg}$ and $W_{4,8kg}$. All the weights are linear proportional. This makes the problem of finding the number of weights easier since the same total weight can be achieved regardless of which weights are used. The mapping the ballast adjustments will be solved separately for each point of adjustment.

The first step is to check the how many of the largest weights that can be added. This is because it is desirable to use as few weights as possible. The calculated mass adjustment, $m$, is divided by the largest available weight, $W_{4,8kg}$. The lower integer solution of the division gives number of weights required, $n_{4,8kg}$:

$$\lfloor n_{4,8kg} \rfloor = \frac{m}{W_{4,8kg}} \tag{5.22}$$

Then, the remaining mass that has to be added, $m_{remain}$, is found:

$$m_{remain} = m - (\lfloor n_{4,8kg} \rfloor W_{4,8kg}) \tag{5.23}$$

The remaining mass, from Equation 5.23, is then divided by the next largest weight, $W_{2,4kg}$, to find how any of the middle weight are needed:

$$\lfloor n_{2,4kg} \rfloor = \frac{m_{remain}}{W_{2,4kg}} \tag{5.24}$$

Then the still reminding mass, $m_{lastremain}$, is found:

$$m_{lastremain} = m_{remain} - (\lfloor n_{2,4kg} \rfloor W_{2,4kg}) \tag{5.25}$$

Then, the last remaining mass, from Equation 5.25, is divided by the smallest weight, $W_{1,2kg}$ (see Equation 5.26). Here, both the lower integer are also is used to make sure that not too much weight is added, which will possibly make the AUV negatively buoyant.

$$\lfloor n_{1,2kg} \rfloor = \frac{m_{lastremain}}{W_{1,2kg}} \tag{5.26}$$

This process is repeated for each of the four adjustable points on the AUV. Based on these results, the system will then inform an human operator about the needed adjustments and tell the operator which weight should be added or removed where.

# Part III

# TESTING, RESULTS AND IMPROVEMENTS

# Chapter 6

# System testing

According to the description of this Master Thesis, the tasks in this Master Thesis are as follows:

1. Designing and developing a system that automatically identifies required ballasting for AUVs.
2. Making a test routine to test the system with different ballast errors.

The solution to task 1 has been presented in Chapters 4 and 5. This system solution will then be tested according to task 2. Test routines will be created, which should verify that the performance of the system is in accordance with the system specifications in Section 5.1. This include identifying any ballast error, determine the required vehicle ballasting to achieve a stable equilibrium and map the adjustment for the user. The system testing was planned as follows; the system will be tested with different inputs and the resulting outputs of the system will be analyzed to check how it behaves and performs. The system will only be tested with Kongsberg Maritime's HUGIN 1000.

Each of the mission modes will be tested independently with realistic values to see if they are able to perform their task:

- The first mission mode should identify necessary changes in ballast based on the user inputs entered about the AUV
- The post mission mode should identify ballast errors based on mission data

- The pre mission mode should determine necessary changes in ballast based on the processed mission data

Lastly, the whole system, with all its mission modes, will be tested to see if the system is able to perform all its tasks when all the mission modes are used according to sequence presented in Section 5.2.

## 6.1 First mission mode testing

The first mission mode will be tested with different user inputs that yield different cases of ballast errors, which are weight/buoyancy imbalance and pitch and roll errors. The weight of the AUV is set as the weight of the HUGIN 1000, 1 498 kg (see Table 3.1). The different test cases are achieved by entering inputs that correspond to different weight distributions according to what ballast error should be simulated (see Appendix F.1). For all the cases, the rope location will be set 1 meter in front of and behind the CO of AUV. The water temperature will be set to 4 °C and the salinity will be 35 ppt, which is the average salinity of ocean water.

The first mission should, based on the inputs, identify any present ballast errors and determine a suitable ballast adjustment. The resulting proposed ballast adjustments are the outputs that will be analyzed to determine if the first mission works correctly.

The results of this testing are presented in Section 7.1 along with discussions of the results.

## 6.2 Post mission mode testing

For the testing of the post mission mode, the mission data provided by Kongsberg Maritime will be used (see Section 3.2). These are realistic mission data from an AUV that was not optimally ballasted; the AUV has errors in depth, pitch and roll (see Appendix F.2). The output of the post mission mode will be the identified ballast errors, which will be analyzed to see if the post mission mode works correctly.

The results of this testing are presented in Section 7.2 along with discussions of the results.

## 6.3 Pre mission mode testing

The pre mission mode will be tested with different cases of possible ballast errors identified by the post mission mode (see Appendix F.3). The cases will be implemented in a ballasting file to simulate that these errors have been identified by the post mission mode. Then the pre mission will determine suitable ballast adjustments. The resulting proposed ballast adjustments are the outputs of the pre mission mode that will be analyzed to determine if the pre mission works properly.

The results of this testing are presented in Section 7.3 along with discussions of the results.

## 6.4 Whole system testing

Lastly, the whole system, with all its mission modes, will be tested to see if the system is able to perform all its tasks as a unit. For this complete test, the mission data provided by Kongsberg Maritime are used in the post mission mode part of the system, and related and suitable inputs will be created for the first mission mode. The water temperature is set to 4 °C and the salinity will be 35 ppt in the first mission mode, while the post mission mode will change to temperature to about 6.54 °C and the salinity to 34.49 ppt in the ballasting file based on the mission data.

The sequence of the testing will follow the sequence of the system (see Figure 5.1). The first mission mode will identify ballast errors based on user inputs and the calculated adjustments will be stored in the ballasting file. The post mission mode will then use the mission data to identify ballast errors and store these errors in the ballasting file. The pre mission mode will based on the data stored in the ballasting file determine new suitable ballast adjustments. This complete test of the system checks that the sequence in which the system is executed works and that all the mission modes use the ballasting file as intended.

The results of this testing are presented in Section 7.4 along with discussions of the results.

# Chapter 7

# Results and discussion

In this chapter, the results of the Master Thesis work will be presented, which includes the results of the system tests (see Section 6), analysis of test results and discussions about the system's performance. The results of the system testing will be presented stepwise, with continuous discussions of the results, for each mission mode in this chapter and in Appendix G.

## 7.1 Results of the first mission mode testing

The results of the tests performed on the first mission mode will be presented in this section and in Appendix G.1. The results of the different test cases are presented in two tables and several bar plots where the x-axes represent the different test cases. The test cases that were created for the testing are listed in Table F.1. These values were entered into the first mission mode of the system.

The accurately calculated ballast adjustments, based on the CG shift approach (see Section 5.4.1), are listed in Table G.1. However, these exact adjustments are impossible to achieve with available adjustment weights (see Section 5.4). The ballast adjustments that have to be mapped to match the available weights. The mapped ballast adjustments are listed in Table G.2. These are the actual weights that will be added.

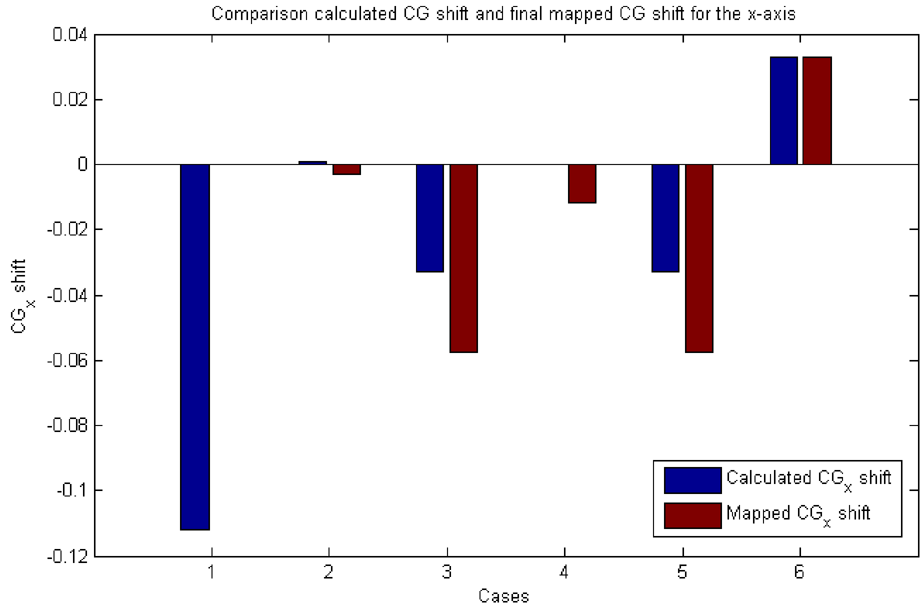


Figure 7.1: The calculated and mapped CG shifts for the x-axis for cases 1 to 5b

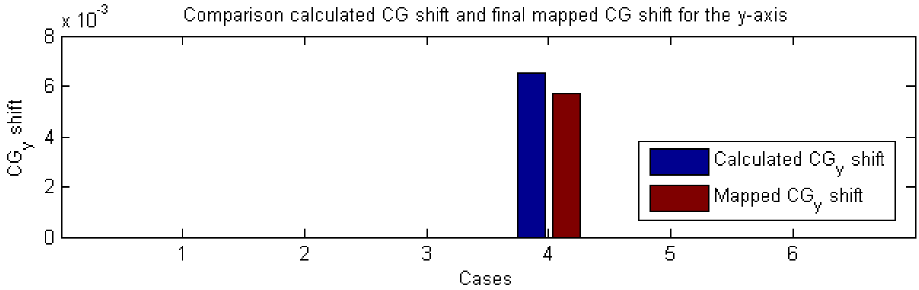


Figure 7.2: The calculated and mapped CG shifts for the y-axis for cases 1 to 5b

The result of the ballast adjustments with the calculated and the mapped values are further checked by studying if they make the CG coincide with the CB. The resulting CG is the initial CG added with the CG shift from the ballast adjustment. The CG shifts are presented in the plots in Figures 7.1 and 7.2, which show the CG shifts based on the calculated ballast adjustments and the actual mapped ballast adjustments. In the plots, only the cases that yield a ballast adjustment are used, which are cases 1 to 5b, where the case numbered with 6 in the plots is actually case 5b.

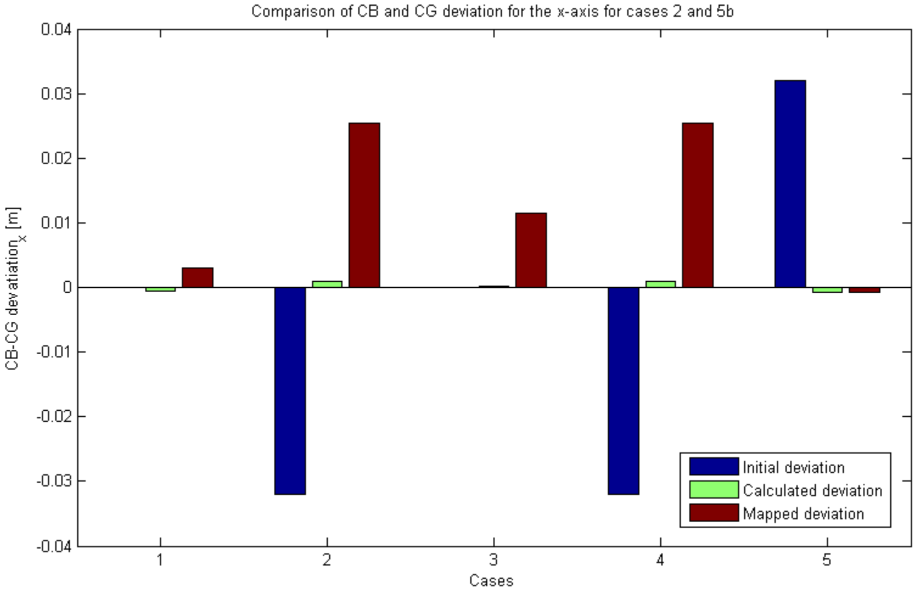


Figure 7.3: The CB and CG deviation along the x-axis after ballast adjustments

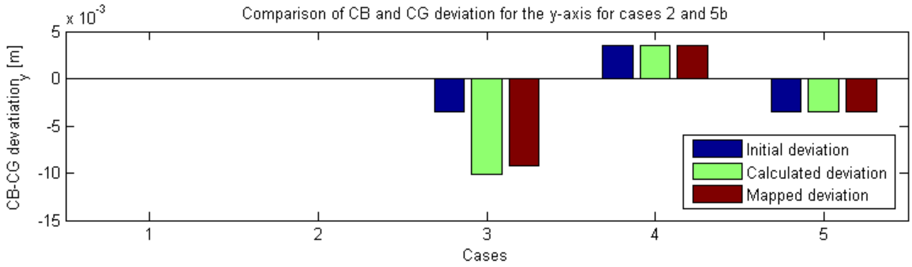


Figure 7.4: The CB and CG deviation along the y-axis after ballast adjustments

The first mission mode's performance can be evaluated by viewing the resulting deviation between the CB and the CG with the ballast adjustments determined by the first mission mode for the different test cases. This can be seen in the plots in Figures 7.3 and 7.4, which show the deviation between the CB and the CG before and after the ballast adjustment. The plots show the results of test cases 2 to 5b. The blue bars indicate the initial CB-CG deviation before any ballast adjustments. The green bars indicate how the CB-CG deviation would have been if the exactly calculated adjustments could have been used. The red bars indicate the CB-CG deviation after ballast adjustments based on the mapped ballast adjustment, which is the actual ballast adjustment with the available weights. The plots indicate the orientation errors with the CB-CG deviations along the x- and y-axis. The deviations are in the magnitudes $10^{-2}$ of a meter for pitch and $10^{-3}$ of a meter for the roll, which is relative little for a vehicle with length 5.23 m, diameter 1 m and weight 1 498 kg. This indicates that the orientation errors are small.

In most cases, like case 3, 5a and 5b, the CB-CG deviations along the x-axis have decreased, meaning that the ballast adjustment will reduce the pitch errors. However, other cases it can be seen that the CB-CG deviation have increased after the ballast adjustment. Especially in test case 4, where there only is a roll error, the CB-CG deviation along the x-axis increases. This is because the system makes a trade-off, it sacrifices a little accuracy along the x-axis to improve the error along y-axis. It is impossible to get the CB and CG to completely coincide when using the available adjustment weights. When a certain amount of weight has to be added to decrease the weight/buoyancy imbalance, which is the top priority, there might be a small error in orientation left.

It should be noted that it is difficult to adjust for errors in roll. This is because the arms of the weight moment from the added weight are very short. The resulting moment of the added weights will therefore be very small compared to the total weight and inertia of the AUV. This can be seen in plot 7.4. In test cases 4, 5a and 5b, where there is a significant roll error, the ballast adjustments are not able to improve the deviations in roll. However, it should be noticed that they are only off by 1 cm and less, while the weight/buoyancy imbalance, at the same time, is significantly reduced.

When using an initial weight of 1498 kg for the HUGIN 1000 with the water temperature of 4 °C and salinity of 35 ppt, the required ballast adjustment to make the vehicle neutrally buoyant is 69.6 kg. As seen in Table G.2, a little less than 69.6 kg is added in all cases. This is in correspondence with the priorities for the ballast adjustments in Section 5.4. Making sure that the vehicle does not become negatively buoyant is the top priority. In the plot in Figure 7.5, the weight/buoyancy balances of the vehicle based on the mapped ballast adjustments are shown. The plot shows all the cases 1 to 5b, where the case numbered with 6 in the plot is test case 5b. Positive values indicates that the AUV is positively buoyant, while negative values indicates that the AUV is negatively buoyant. In plot 7.5 it can be seen that the vehicle maintains a slightly positive buoyancy after the ballast adjustment.

That the vehicle is positively buoyant during the first mission can be an advantage as this will act as an extra safety in the event of emergencies, because then the vehicle will naturally float up to the surface. In addition, it will leave room for adjustments of the orientation later in the pre mission mode without making the vehicle negatively buoyant. After the first mission, more weights can be added to certain points of adjustment based on ballast errors identified by post mission mode.

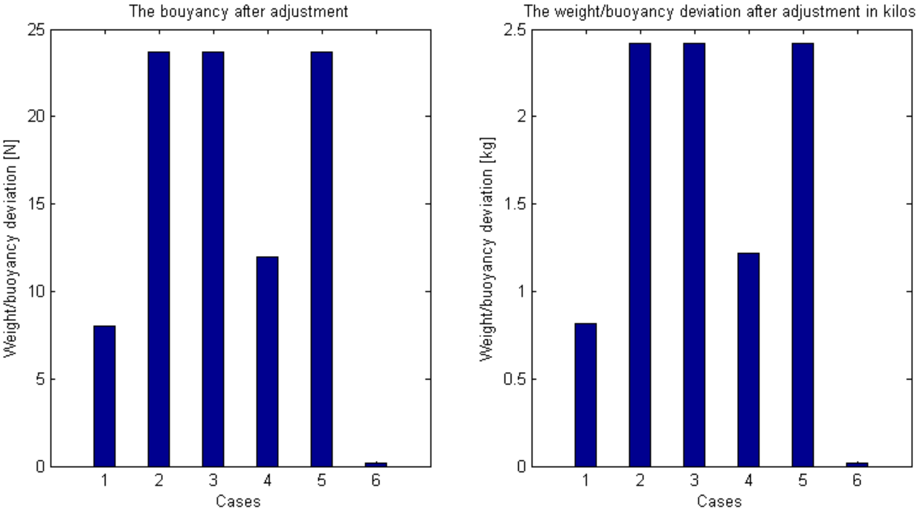


Figure 7.5: The weight/buoyancy balance after the ballast adjustment

The results show that the first mission mode is able to determine suitable ballast adjustments based on the weight measurements entered. However, the limited number of different sizes of adjustment weights significantly reduces the performance of the first mission mode. All the available weights are proportional linear, which reduces the number of possible total weights that can be achieved by combining them. The accurately calculated ballast adjustments, listed in Table G.2, cannot be completely achieved with the available weights. The ballast adjustments have to be mapped to match the available weights. The mapped adjustments will not yield optimal adjustments in every case, however, they will improve the ballast errors. The difference between the resulting CB-CG deviation for the accurately calculated and mapped ballast adjustment can clearly be seen in plot 7.3. To further improve the ballasting an additional adjustment weight could be added (see Section 8.1).

The performance of the first mission mode is, moreover, affected by the assumptions and simplifications made in the design (see Section 5.4.1). Particularly the calculations of the CG introduce inaccuracies. Both the CG and the CG shift are calculated as systems of particles. This method will not yield the exact positions of the CGs since the mass of the vehicle is not located in certain points. The mass is non-homogeneously distributed in the vehicles because of their payloads' different sizes and weights.

## 7.2 Results of the post mission mode testing

With the ballast adjustment performed in first mission mode, the hope is that ballast of vehicle is close to optimal with only small errors in weight/buoyancy, pitch and roll for its first mission. Any errors in the ballast should then be identified by the post mission mode. The post mission mode will process the mission data that the vehicle has collected during its mission. To check if the post mission mode is able to do this, a test was done in accordance with the test routine presented in Section 6.2. The results of the test will be presented in this section with Table 7.1, where the identified water properties and ballast errors are listed.

| | Temperature | Salinity | Depth error | Pitch error | Roll error |
|---|---|---|---|---|---|
| Initial state | 4 | 35 | Unknown | Unknown | Unknown |
| Post mission | 6.5456 | 34.498 | 8.7594 | -0.59959 | 0.73636 |

Table 7.1: The identified properties and ballast errors for the testing of the post mission mode

The identified errors in Table 7.1 are checked by comparing them with the plots in Figures F.1, F.2 and F.3:

- Plot F.1 shows that the vehicle does not completely achieve the commanded depth, it does not reach all the way down. The post mission mode has correctly identified this as a positive depth error.

- Plot F.2 shows that the vehicle's measured pitch is slightly less than the commanded pitch. The post mission mode has correctly identified this as a negative pitch error.

- Plot F.3 shows that the vehicle's measured roll is overall slightly positive. The post mission mode has correctly identified this as a positive roll error.

The post mission mode has thus managed to identify the ballast errors that were present in the mission data. In addition, the post mission mode has found a more accurate water temperature and salinity for the water on the operational depth. The post mission then found and loaded the correct ballasting file, which it updated with the new data.

## 7.3 Results of the pre mission mode testing

The results of the test on the pre mission mode will be presented in this section and in Appendix G.2. The results of the test cases are presented in a table and several scatter plots. The test cases that were created for this testing are listed in Table F.2. These values represent possible ballast errors identified by the post mission mode, and were entered into a modified ballasting file, which was used by the pre mission mode for the testing.

The resulting mapped ballast adjustments are presented in Table G.3. These results are illustrated in the plots in Figure 7.6, which show the ballast errors and the mapped ballast adjustment. The stars represent the ballast errors, their positions indicate pitch and roll errors, while their colors indicate the depth error. The dots represents the different adjustment point, their colors indicates the weight adjustment made in the point. The full explanation of the plots can be seen in Appendix G.2.

The pre mission mode works by doing small ballast adjustments between missions, improving the ballast a little every time based on the identified ballast errors. The 7.6 plots shows that the ballast adjustment mapped by the pre mission mode tries to counteract the ballast errors identified by the post mission mode. The ballast errors include depth, pitch and roll errors, based on these values ballast adjustment will be mapped using the approach explained in Section 5.4.2 and the tables shown in Appendix E.

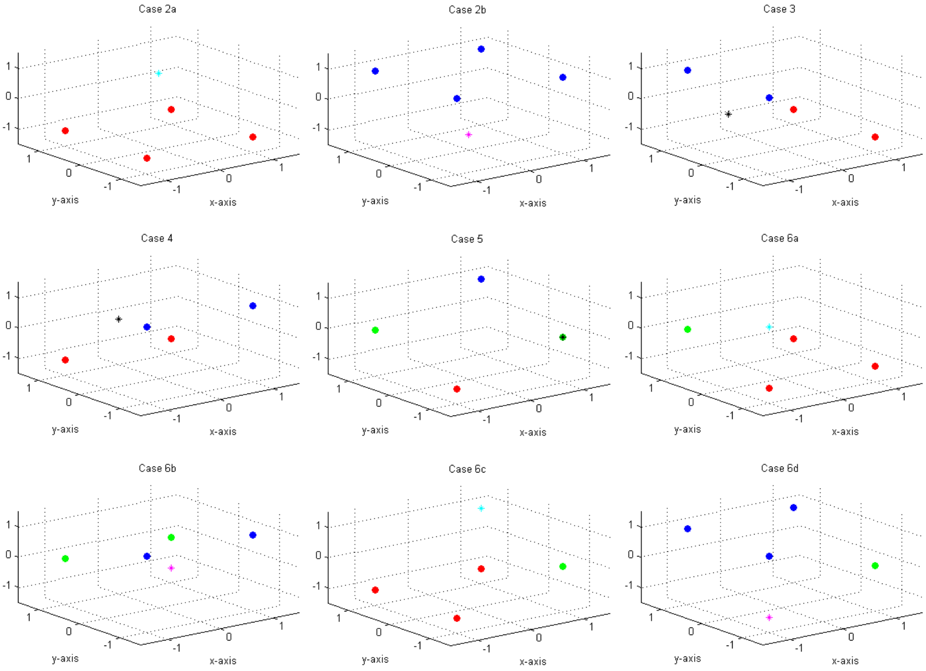


Figure 7.6: The ballast errors and the mapped adjustments from the pre mission mode testing

By studying both Table G.3 and the plots in Figure 7.6, it can be seen that:

- For test cases 2a and 2b, where there only are a depth error, the weight is distributed equally between points of adjustment:
    - For case 2a, where the vehicle is positively buoyant, weight is added.
    - For case 2b, where the vehicle is negatively buoyant, weight is removed.
- For test cases 3 to 5, where there are only orientation errors, an equal amount of weight is added/removed from the different point of adjustment to change the orientation of the vehicle without changing the overall weight.
- For test cases 6a to 6d, where there are depth and orientation errors, the overall ballast adjustment is non-zero and the weight is distributed unequally at the points of adjustment to achieve the necessary adjustment.

## 7.4 Results of the whole system testing

The complete system test was done in accordance with the test routine presented in Section 6.4. Table 7.2 shows the ballast adjustment determined in the first and pre mission mode. The first column represents how much more weight should be added overall, while the other columns represent how much weight should be added to each point of adjustment.

| | Total | Fore/Star | Fore/Port | Aft/Star | Aft/Port |
|---|---|---|---|---|---|
| First, calculated | 69.6 | 10.0 | 10.0 | 24.8 | 24.8 |
| First, mapped | 67.2 | 9.6 | 9.6 | 24.0 | 24.0 |
| Pre, mapped | 4.8 | 0.0 | 1.2 | 1.2 | 2.4 |

Table 7.2: The resulting ballast adjustments for the testing of the whole system

The results of the post mission mode will be the same as in Table 7.1 since the same mission data are used.

The effects of the ballast adjustment in the first mission mode are illustrated in the plots in Figure 7.7, which show the CG-CB deviations initially, with the calculated adjustment and with the mapped and actual adjustment for the x- and y-axis. In addition, a plot of the weight/buoyancy balance initially, with the calculated adjustment and with the mapped adjustment is shown. In terms of the weight/buoyancy balance, it is considerably improved. It is not entirely neutral with the mapped adjustment, it remains slightly positive, which is in accordance with the system specifications. The weight/buoyancy balance should rather be positive than negative.

The ballast adjustment determined by the first mission mode does also significantly improve the ballast error along the x-axis as seen in plot 7.7. Before the ballast adjustment the CG was off by about 5.4 cm along the x-axis, while afterwards it was only off by about 0.4 cm with the mapped adjustment. Note that the calculated adjustment would have given a better ballast adjustment than the mapped adjustment, which is limited by the available weights. For the y-axis, however, the error is not improved by either the calculated and mapped adjustment, nor is it worse. The reason for this is that the moment arms of the weights added are relatively short. Counteracting roll errors are therefore difficult as a lot of weight is required to achieve a change. When the payloads in the vehicle are mounted particularly care should be taken when distributing weight along the y-axis since errors in roll is harder to correct.

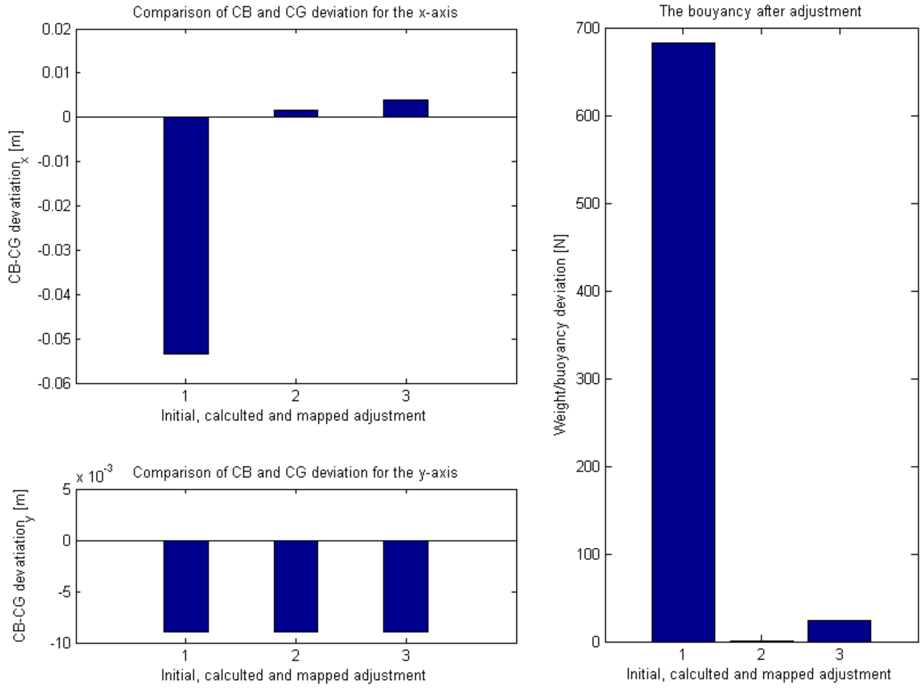


Figure 7.7: To the left; the CB-CG deviations for the x- and y-axis, to the right; the weight/buoyancy balance, for the whole system testing

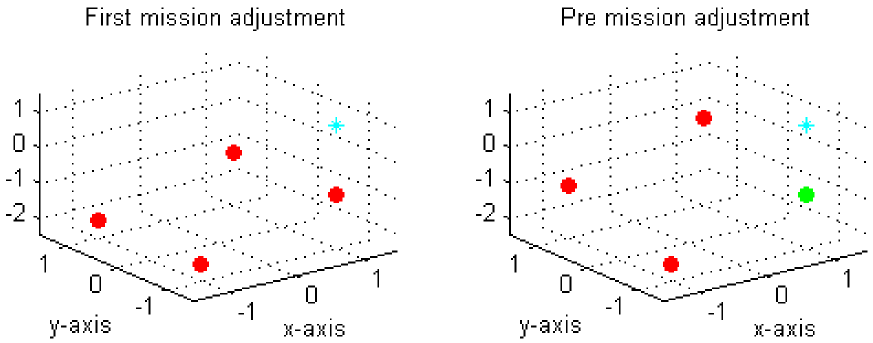
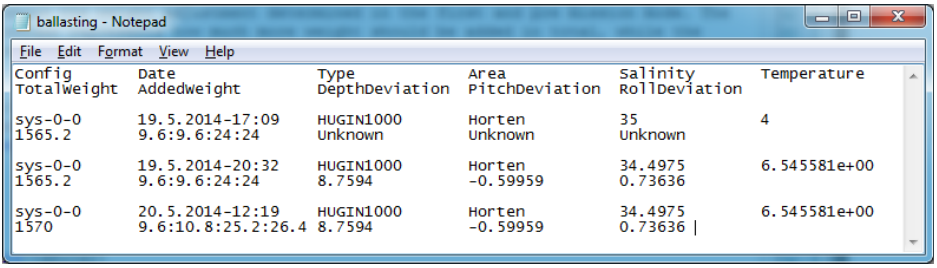


Figure 7.8: The ballast errors and the mapped adjustments from the tests of the whole system

The exact size of the resulting ballast correction in the pre mission mode is not known. However, the mapped ballast adjustments in the pre mission mode and the first mission mode are illustrated in the plots in Figure 7.8, which show the ballast errors (the stars) and the mapped weight adjustments (the dots). The full explanation of the plots can be seen in Appendix G.2. The ballast errors in both the first and pre mission mode include depth, pitch and roll errors. The 7.6 plots show that the ballast adjustment mapped by both mission modes try to counteract the ballast errors by distributing the weight between the four points of adjustment. The weight distribution is in the first mission mode determined by the using the CG shifting approach presented in Section 5.4.1, while the pre mission mode does a small ballast adjustment based the ”slow control loop” approach explained in Section 5.4.2.

The resulting ballasting file of the whole system test can be seen in Figure 7.9. The ballasting file is the result of running the three mission modes according to the sequence in Figure 5.1 and the test routine planned in Section 6.4. In Figure 7.9, it can be seen that each mission mode has performed its task and stored the necessary data in the file. The second row is the product of the first mission mode, the third row is from the post mission mode and the fourth is from the pre mission mode.



```
Config       Date                  Type            Area            Salinity        Temperature
TotalWeight  AddedWeight           DepthDeviation  PitchDeviation  RollDeviation

sys-0-0      19.5.2014-17:09       HUGIN1000       Horten          35              4
1565.2       9.6:9.6:24:24         Unknown         Unknown         Unknown

sys-0-0      19.5.2014-20:32       HUGIN1000       Horten          34.4975         6.545581e+00
1565.2       9.6:9.6:24:24         8.7594          -0.59959        0.73636

sys-0-0      20.5.2014-12:19       HUGIN1000       Horten          34.4975         6.545581e+00
1570         9.6:10.8:25.2:26.4 8.7594          -0.59959        0.73636
```

Figure 7.9: The resulting ballasting file of the whole system test

The results of the testing verifies that the system performs accordingly to the requirements of Kongsberg Maritime and the specifications in Section 5.1 with the limitations in Section 1.2.1 and the design issues discussed in Section 4. The system has proved that it is able to identify ballast errors of different magnitudes and types and that it is able to determine suitable ballast adjustments.

# Chapter 8

# Improvements for the system

During the work with this Master Thesis several areas of possible improvements and extensions were researched, which include aspects that will make the system more accurate, more general and fully-automatic. These improvements and extensions will be presented in this chapter.

## 8.1 New adjustment weight

As discussed in Chapter 7, the accuracy of the ballast adjustments are significantly reduced by the available adjustment weights (see Section 3.1). All these weights are linear proportional, which makes it impossible to achieve the exact calculated ballast adjustment. By acquiring a weight that is not linear proportional to the already existing weights, and smaller than 1 kg, the ballast adjustment could be even more fine-tuned. The resulting mapped ballast adjustment in the first mission mode with a 0.5 kg weight will be improved.

The improvement with this new 0.5 kg weight is shown in the plots in Figures 8.1 and 8.2, which show the deviation between the CB and the CG before and after the ballast adjustment. The test cases from the testing of the first mission mode are reused when testing out the new weight (see Appendix F.1). The dark blue bars indicate the initial CB-CG deviation before any ballast adjustment. The light blue bars indicate how the CB-CG deviation would have been if the exactly calculated adjustments could have been achieved. The yellow bars indicate the

CB-CG deviation after ballast adjustments based on the mapped ballast adjustment with only the old weights, while the red bars indicate the CB-CG deviation with the new 0.5 kg weight. In most cases, the red bars are smaller than the yellow bars, which suggest that adding the new 0.5 kg weight will fine tune the ballasting.

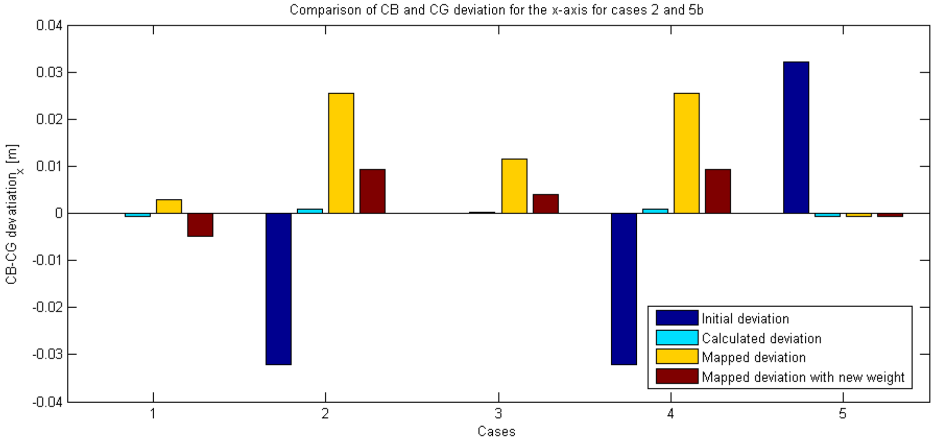


Figure 8.1: The CB and CG deviation along the x-axis after the ballast adjustment with the new weight

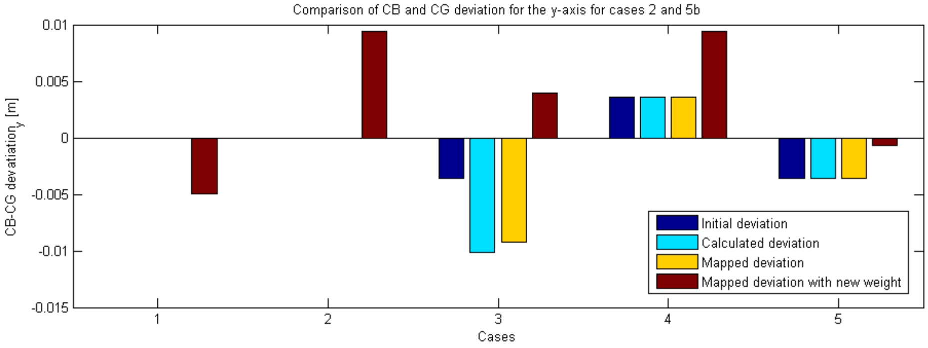


Figure 8.2: The CB and CG deviation along the y-axis after the ballast adjustment with the new weight

## 8.2 Determining ballast adjustments with optimization

In the implemented system, presented in Chapter 5, uses the two approaches explained in Sections 5.4.1 and 5.4.2 to determine a suitable ballast adjustment. The ”slow control” approach in Section 5.4.2 is a very specialized approach, which was designed to determine ballast adjustments based on depth, pitch and roll measurements collected by the AUV during a mission. Although the CB is known (see Section 3) and the gravity force and buoyancy can be calculated (see Section 2.3 and 2.4), the CG of the AUV is unknown, which is why this approach was chosen. None of the mission data collected during the mission give a direct value or a ratio for the mass distribution. They only give an indication of the how the mass is distributed by observing the errors in pitch and roll (see Section 5.3). Unfortunately, there is no direct mathematical or physical relationship between the error angles and the size of the mass distribution. The pitch and roll can therefore be used to determine any ballast errors.

By installing a CG measurement instrument in their AUVs, Kongsberg Maritime could utilize a more generalized and elegant approach for calculating the required ballast adjustment by using optimization. If the CG is known, determining the required ballast adjustment can be formulated as an optimization problem where the objective is to get the CG as close as possible to the CB while the weight is approximately equal to the buoyancy force. The optimization problem will be limited by how much the weight can be added. The constraints on the optimization problem will be:

1. the weight of the AUV with the added weight should not be significantly smaller or larger than the buoyancy force acting on it
2. only three weight sizes are available for HUGIN 1000 (it is assumed that there are infinitely many available of each size), all are linear proportional

Constraint no. 1 will be a formulated as an inequality constraint, $c_i(x) \geq 0, i \in \mathcal{I}$. The total weight, which is the weight of the AUV plus the added adjustment weight, should be equal or smaller than the buoyancy force. The optimal case would be that the total weight is equal to the buoyancy force to satisfy the first condition of a stable equilibrium with neutral buoyancy. However, because of constraint no. 2, that maybe impossible in some cases. The first constraint is therefore expanded to an inequality constraint where the weight can be smaller than the buoyancy force too. When the weight is smaller than the buoyancy force, the AUV will in a case emergency float up with no thrust applied. If the inequality constraint was set with weight equal or greater than the buoyancy force, the AUV could in a case emergency sink if no thrust are applied.

The first constraint will be:

$$B - W_{AUV} - m_1 - m_2 - m_3 - m_4 \geq 0 \tag{8.1}$$

Constraint no. 2 is a set of integrality constraints. Each integrality constraint is a set of integers $x_i \in \mathbb{Z}$. In this case, the set, $\mathbb{Z}$, of integers are the available weights, which are integers in the in sense that they are finite values. Since the weights are all linear proportional, they could be given by; n × the smallest weight. Optimization problems with integrality constraints are called integer programming problems (see Section 2.8).

The second constraint will be:

$$m_1 \in n \times w_{smallest}$$

$$m_2 \in n \times w_{smallest}$$

$$m_3 \in n \times w_{smallest}$$

$$m_4 \in n \times w_{smallest}$$

Where $w_{smallest} = 1.2$ kg and $n = 0, 1, 2, \ldots, m$.

Because the variables of this optimization problem are restricted integer constraints, the problem is an integer programming problem (see Section 2.8).

A possible formulation of the objective function is:

$$f(x, y, z) = abs(CG_{(x,y,z)} - CB_{(x,y,z)}) \tag{8.2}$$

The CB has known, fixed and numerical values for the three axes, $x_b$, $y_b$ and $x_b$. The CG, however, is not fixed and can be formulated was function of position vectors and mass distribution. The position vectors is known and fixed, so the CG can only be shifted by changing the mass distribution. Therefore, to minimize the objective, the mass distribution of the AUV must be changed by adding or removing weights at the four points of adjustment (see Section 3.1). The CG can be expressed, as in Section 2.4, with two terms giving the $CG_{new}$, which should be as close as possible to the CB:

$$\begin{aligned} CG_{new} &= CG_{old} + CG_{shift} \\ &= \frac{1}{M_{AUV}}(\sum m_i r_i) + \frac{1}{M_{shift}}(\sum m_i r_i) \end{aligned} \tag{8.3}$$

Where $M_{AUV}$ is the net weight of the AUV and $M_{shift}$ is the sum of $m_i$ in the adjustment term, which yields the CG shift.

The complete optimization problem, based on Equations 8.2 and 8.3, will be:

$$\begin{aligned} \min_{x,y,z} \quad & f(x,y,z) = abs(\frac{1}{M_{AUV}}(\sum m_i r_i) + \frac{1}{M_{shift}}(\sum m_i r_i) - CB_{(x,y,z)}) \\ \text{s.t.} \quad & B - W_{AUV} - m_1 - m_2 - m_3 - m_4 \geq 0 \\ & z_g - z_b \geq d, \text{ d is the desired distanse between } CG_z \text{ and } CB_z \\ & m_1 \in n \times w_{smallest},\ n = 1, \ldots, 100 \\ & m_2 \in n \times w_{smallest},\ n = 1, \ldots, 100 \\ & m_3 \in n \times w_{smallest},\ n = 1, \ldots, 100 \\ & m_4 \in n \times w_{smallest},\ n = 1, \ldots, 100 \end{aligned} \tag{8.4}$$

The variables in Equation 8.4 are the $m_i$ variables. By changing these variables the CG$_{new}$ will be moved. However, just minimizing Equation 8.2 will not necessary yield a stable state of equilibrium, but rather a neutral state (see Section 2.6). An additional constraint has therefore been included on the z-axis to ensure that there is enough distance between the CB and the CG to cause stability. Without this constraint the z-coordinates of the CG and CB might end up coinciding.

The optimization problem is an integer linear programming problem (see Section 2.8) since all the variables, $m_1$, $m_2$, $m_3$ and $m_4$, are restricted to certain discrete values. The problem is therefore NP-hard (see Section 2.8). Another problem with this formulation of the objective function is that the $r_i$ is not a specific point, thus making the solution less accurate.

Another possible formulation is to use the restoring force and moment vector as the objective function (see Section 2.5 and Equation 2.10):

$$f(x,y,z) = abs(g(\eta)) \tag{8.5}$$

Expression 2.10 includes all the terms for the stable equilibrium state:

- $W - B$, which should be as close to zero as possible, but not positive
- $x_g - x_b$, which is the x values of respectively the CG and the CB, and should be as close to zero as possible
- $y_g - y_b$, which is the y values of respectively the CG and the CB, and should be as close to zero as possible
- $z_g - z_b$, which is the z values of respectively the CG and the CB, and should be a positive value (the z-axis is positive downwards)

This objective function does therefore include both conditions for stable equilibrium with neutral buoyancy (see Section 2.6). The expression also includes the pitch and roll angles, which is known (see Section 3.2). By minimizing weight/buoyancy balance and distances between the x- and y-coordinates of the CG and CB in the absolute of Equation 2.10, the resulting expression will be Equation 2.13, which corresponds to the stable equilibrium state with neutral buoyancy. Using this formulation the first constraint, the inequality constraint, will be directly handled inside the objective function.

As the integer constraints still applies, this problem formulation will also be an integer programming problem and therefore NP-hard. Another drawback with this formulation is that the problem becomes nonlinear because of the trigonometric functions. This makes the problem an integer nonlinear programming problem. However, as the angles in this case are very small, small-angle approximation can be used to linearize the problem. The angles will be arguably small since extensive ballast adjustments are carried out in the first mission mode, so it is assumed that the angular errors are small enough for this linearization. With the linearization the problem is reduced to the integer linear programming problem.

With the small-angle approximation Equation 2.10, and therefore the objective function, becomes:

$$f(x,y,z) = abs(g(\eta)) = abs(\begin{bmatrix} (W-B)\theta \\ -(W-B)\phi \\ -(W-B) \\ -(y_gW - y_bB) + (z_gW - z_bB)\phi \\ (z_gW - z_bB)\theta + (x_gW - x_bB)\phi \\ (x_gW - x_bB)\phi - (y_gW - y_bB)\theta \end{bmatrix}) \tag{8.6}$$

Where the $W_{AUV}$ and $W_{shift}$ are the weight of the AUV and the weight of the adjustment, the $B$ is the buoyancy force acting on the AUV, the $\phi$ and $\theta$ are the pitch and roll angles, the $x_g$, $y_g$ and $z_g$ are the CG coordinates and the $x_b$, $y_b$ and $z_b$ are the CB coordinates.

Expression 8.6 must be expanded to include the ballast adjustment. The expression can with the ballast adjustment be rewritten to:

$$f(x,y,z) = abs(\begin{bmatrix} (W_{AUV} + W_{shift} - B)\theta \\ (B - W_{AUV} - W_{shift})\phi \\ B - W_{AUV} - W_{shift} \\ (W_{AUV} + W_{shift})(z_g\phi - y_g) - B(y_b + z_b\phi) \\ (W_{AUV} + W_{shift})(z_g + x_g\phi) - B(z_b + x_b\phi) \\ (W_{AUV} + W_{shift})(x_g\phi - y_g\theta) + B(y_b\theta - x_b\phi) \end{bmatrix}) \tag{8.7}$$

By implementing this objective function with a suitable optimization algorithm that can handle the constraints, the ballast adjustment problem can be solved as one problem. In the implemented system in Chapter 5, the weight/buoyancy balance, pitch and roll are handled independently and uncoupled. However, in this optimization approach they will be handled together with respect to each other, which could yield a better solution.

## 8.3 Active ballast systems

The ballast system presented in Chapter 5 is a static ballast system, which was what Kongsberg Maritime requested. Nevertheless, during the work with the static ballast system, articles and books with theory on active ballast systems was read (see Section 2.7.2). They presented interesting theories and opened up for new possibilities concerning the effectiveness of the system. Suggestions for how to implement an active ballast system for the HUGIN 1000 were therefore included in this Master Thesis. These systems are meant to run in real-time during missions.

An active ballast system can be designed to change the weight/buoyancy balance of the vehicle by using one of the four first methods for active ballasting mentioned in Section 2.7.2 or change the pitch and roll by using one of the two last methods for active ballasting. In Sections 8.3.2 and 8.3.3, active ballast systems with controllers for buoyancy, pitch and roll are presented and discussed. These controllers were inspired by articles [9] and [19]. A literature review of these articles are given in Section 8.3.1.

### 8.3.1 Literature reviews

Although not requested in the Master Thesis description, a small literature survey was conducted to look at the possibility to expand the system from a static, non-real-time system to an active, real-time system. The research showed that several systems for identification and automatic ballast adjustment during missions in real time exist. In this chapter the results of the survey will be presented.

#### "Automated Ballast Tank Control System for Autonomous Underwater Vehicles" by Woods, Bauer and Seto

Woods, S.A., Bauer, R.J. and Seto, M.L. present an autonomous control system for ballast tasks in the article "Automated Ballast Tank Control System for Autonomous Underwater Vehicles" [18]. They suggest that ballast tanks will be used to adjust the weight and CG of AUVs by filling the ballast tanks with water. In the article two unique variable ballast systems (VBS) are presented, which can be used to control the weight/buoyancy balance and pitch of an AUV. With these VBSs the controllability of AUVs will increase. The first VBS controller will control the depth and vertical velocity by adjusting the weight of the AUV, while the second controller will aim to decrease the depth and pitch angle error by moving the CG.

The first VBS controller is a proportional derivative (PD) VBS depth controller. The controller compares the measured depth to a set depth that are desired, based on this deviation the controller will fill or empty the ballast tanks. As stated by the authors of the article, this PD VBS controller provides depth control, but not pitch control. To gain pitch control, the authors of the article propose what they call a VBS $x_G$ shifting controller. For this controller to work, the AUV has to fitted with two ballast tanks, one in the fore and one in the aft, which can be filled and empty independently. The CG is then moved along the x-axis by filling/emptying the tanks at different rates and with different volumes. The article presents the results of tests done to check if the presented VBSs controllers will achieve the set point depth and pitch angle. The authors state that the tests prove that they are capable of this. However, the authors also note that the two controllers cannot be used together and yield efficient performance as they utilize the same ballast tanks for competing purposes.

The system that has been developed and implemented in this Master Thesis, presented in Chapter 5, will only be used pre and post mission. It is a static ballasting system, while this article deals which systems that are going to run continually during a mission as an active ballasting system. It is the first VBS controller, presented in this article, which was the inspiration for the proposed active weight/buoyancy controller in Section 8.3.2. The VBS $x_G$ shifting controller inspired the proposed active pitch and roll controller in Section 8.3.3.

#### "Analysis and development of a buoyancy-pitch based depth control algorithm for a hybrid underwater glider" by Claus, Bachmayer and Cooney

The article "Analysis and development of a buoyancy-pitch based depth control algorithm for a hybrid underwater glider" by Claus, B., Bachmayer, R. and Cooney, L., deals with the development of buoyancy and pitch controllers [9]. The article presents two controllers, both based on a depth controller algorithm. The first controller includes both buoyancy and pitch control, and is therefore called a ballast depth controller. The second controller is a pitching depth controller that controls the pitch to achieve a desired pitch.

In their ballast depth controller, the desired depth is achieved by altering the buoyancy and correcting any pitch moments. The controller includes two control loops, one for pitch and one for depth. The pitch controller is a proportional gain feedback controller where the measured pitch is fed back and compared to a set point pitch. The depth controller is a proportional derivative feedback loop that checks the measured depth against a set point depth. Deadbands and saturations have been included in both controller loops. The article explains that this was done to incorporate limitations due to sensor resolution and to protect the vehicle against excessive adjustments. When a signal error is within the deadband, no controller action will be taken. The saturation limits were included to incorporate the limitations in possible changes per control cycle. The controllers' outputs are used as inputs to the internal mass-shifting mechanism that will shift the vehicle's mass to achieve the desired depth. The article concludes that their ballast depth controller, based on performed tests, is able to maintain a desired depth.

According to the authors of the article, the pitching depth controller will exploit an internal mass shifting mechanism to keep the depth of the vehicle constant. The controller, presented in the article, is a proportional derivative feedback loop. The objective of this controller is to counteract the lift forces that occurs when the vehicle is pitching. In this controller, the feedback to the controller is the measured depth, which is used to find the depth error and the depth rate error. The output, limited by a saturation block, is fed to the mass-shifting mechanism that will change the pitch of the vehicle. Based on tests performed, the authors state that this controller are reasonably able to control the vehicle at set point depth while experiencing lift forces.

The authors rounds of by concluding that both controllers work, however, that tradeoffs between them exist in terms of different properties. To take advantage of both controllers, the authors suggest that they can be combined by using a Linear Quadratic Regulator, which can efficiently scale the controller gains based on energy based weighting matrices. The authors focus greatly on how the controllers should contribute to making the vehicle more energy efficient.

The concepts of deadband and saturation are considered in the active ballast systems that are presented in Sections 8.3.2 and 8.3.3. The deadbands and saturations incorporate important physical limitations, like the sensor resolution and possible rate for changing the ballast. In addition, using deadbands and saturation blocks will improve the energy consumption of the vehicle, which is an important and present issue in AUV design. As the AUVs have to carry their entire energy requirement, so making them energy efficient is essential to prolong their operations.

### 8.3.2 A buoyancy controller

HUGIN already has a depth controller, however, the performance of this controller is affected by changes in buoyancy that HUGIN experience during a mission. The buoyancy force on the vehicle changes during a mission because the water's temperature, salinity and pressure changes with changing depth. These changes in buoyancy will affect how the depth controller behaves. If the buoyancy either increases or decreased the depth controller will have to assign more thrust and change the rudder positions to counteract the changes in buoyancy and to regain the desired depth. It can therefore be desirable to have a real-time ballast controller that calculates an optimal weight/buoyancy balance and adjusts the weight accordingly.

The system the already implemented depth controller will become more efficient and accurate during the whole mission even if the water properties change by incorporating a buoyancy controller. The buoyancy controller will also contribute to reducing the resource usage. By making the AUV neutrally buoyant, the desired depth and velocity can be maintained without requiring excessive thruster and rudder use. The buoyancy controller can also be used actively during the diving and surfacing phase to decrease the energy consumption by making the vehicle negatively buoyant during the diving and positively buoyant during the surfacing.

Implementing a buoyancy controller will include installing one or two ballasting tanks with an assembly of valves and pumps that can change the weight/buoyancy balance of the vehicle. According to [14], this can be achieved with a hard ballast tank, a soft ballast tank or an oil-filled reservoir system (see Section 2.7.2). The deciding factor when choosing the type of tank in this case is the space available in HUGIN 1000's hull. Installing a ballasting assembly in the mid-section will come at the expense of the consumer's payloads. To avoid this, the ballasting assembly should if possible be mounted in the standardized constructed fore and aft sections. By splitting the ballasting assembly into two sections in the fore and aft, pitching correction can be implemented too (for more on pitch correction see Section 8.3.3). To change the weight/buoyancy balance the liquid content in both the tanks will be decreased or increased the same rate. If the liquid content of the tanks are not changed with the same rate, the CG of the vehicle will be shifted.

The least space consuming ballasting assembly is the solution with oil-filled reservoirs inside the hull and flexible bladders outside [14]. The bladders will expand when oil is pumped from the inside reservoir tanks, consequently increasing the volume of the vehicle and therefore increasing the buoyancy. The oil will be pumped back and forth between the reservoirs and the flexible bladders based on control inputs from the buoyancy controller. The drawback with using this solution is that the external flexible bladders might change the hydrodynamic properties of AUV and how it behaves in the water. This is undesired for the HUGIN 1000 as it has been designed with a slender-body to minimize the drag on it.

Another drawback with the oil-filled reservoir method is that the buoyancy can only be increased from its initial buoyancy/weight balance. This means that if the buoyancy of the water increases because of changes in the water properties, the system cannot do anything to decrease the buoyancy of the AUV. Therefore, the AUV should initially be slightly negatively buoyant before a mission. This will make the buoyancy controller able to make the AUV both positively and negatively buoyant by shifting the oil between the internal reservoir and external bladders.

Hard ballast tanks or soft ballast tanks can be used instead of the oil-filled reservoir system to avoid the problems with alteration of the AUV's exterior and the limitations in decreasing the buoyancy. The hard or soft ballast tank systems are mounted inside the hull. They rely on air and water, as the weight changing liquid, to change the weight/buoyancy balance of the AUV. Water can easily be collected from and disposed of in the surroundings. Nevertheless, both systems rely on an onboard air supply, which for great depth will have to be of significant dimensions. According to [14], the hard and soft ballast tank systems are not feasible for great depths because of the pressure's affect on air. AUVs that operates at great depths normally utilize the oil-filled reservoir system.

When regarding all the pros and cons of the different ballasting system, the hard tank system seems to be the best choice for HUGIN 1000 as it only goes down to a depth 1 000 m [1]. This ballasting system is preferred, even though it requires the most space, because it does not change the exterior of the AUV. In regards to the lack of space, this can possibly be solved by adding additional and especially designed sections with the active ballasting system to the AUV. It is also advantageous to split the tank into two tanks, one in the fore and one in the aft. However, for Kongsberg Maritime's HUGIN 3000 and HUGIN 4500, which are AUVs that operate down to 5 000 m [2], the oil-filled reservoir system is the best choice because of the depth of their operations.

When the type of ballasting system is chosen, a suitable controller can be designed. For the HUGIN 1000, with the hard ballast tank system, the buoyancy controller is designed as a proportional-integral-derivative (PID) controller (see Figure 8.3). The feedback signals will be the current air/water levels in the tanks and the measurements of temperature, salinity and depth. These values will be used to calculate the current buoyancy force of the buoyancy, which will be compared to the weight of AUV. The error signal will be:

$$e_b(t) = W + w(t) - b(t) \tag{8.8}$$

Where the $e_b(t)$ is the current error in the weight/buoyancy balance, the $W$ is the set point, which is the static total weight of the AUV, the $w(t)$ is the current, calculated weight in the ballast tanks and the $b(t)$ is the current, calculated buoyancy force.

The sensor measurements of the AUV that are needed to calculate the buoyancy force are the water's temperature and salinity, and the depth at which the AUV located. The temperature, salinity and depth would be used to calculate the current water density. With the updated water density, the buoyancy would be calculated with Equation 2.5.

To calculate the current weight of the ballast tanks, a measurement of the water height in the tanks and the water density are needed. The water weight in the tanks can be calculated with Equation 2.7 and known water properties from Section 2.2:

$$W_{tank} = mg = V\rho g = Ah\rho g \tag{8.9}$$

Where $W_{tank}$ is the weight in one of the water tanks, $A$ is the area of the tank, $h$ is the current water height, $\rho$ is the water density and $g$ is the acceleration of gravity (positively downwards). The $A_{tank}$ and $g$ are assumed fixed. The water weight in the tanks will change if the water density changes and the tanks are filled or emptied of water.

The error, $e_b(t)$, should be fed through a deadband, as suggested in [9]. The purpose of the deadband will be, as explained in [9], to include limits due to sensor resolutions and protect the system against excessive adjustments. An accepted value for the buoyancy deadband can be smaller than the acceptable value for weight/buoyancy imbalance in the implemented static ballast system in Chapter 5, which is 1.2 kg (see Section 5.4). It can be smaller in this controller because this system will not be limited by the smallest available weight that can be used for ballast adjustment.

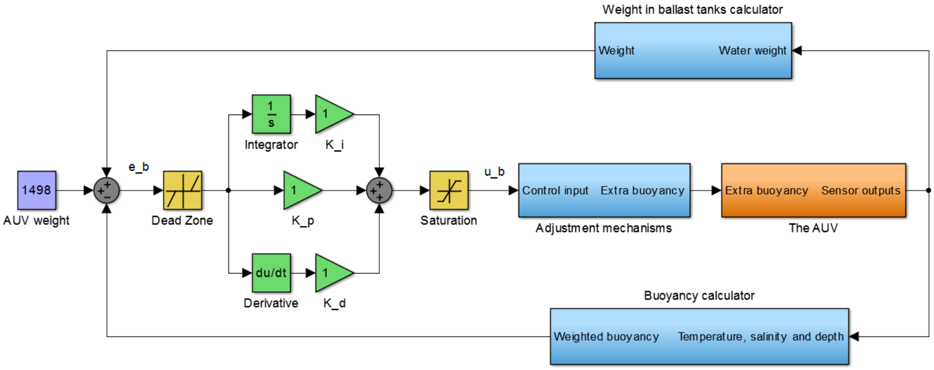


Figure 8.3: The PID buoyancy controller

The controller output of the PID buoyancy controller, $u_b(t)$, will be:

$$\mathrm{u}_\mathrm{b}(t) = K_p e_b(t) + K_i \int_0^t e_b(\tau)\, d\tau + K_d \frac{d}{dt} e_b(t) \tag{8.10}$$

Where $K_p$ is the proportional gain, $K_i$ is the integral gain, $K_d$ is the derivative gain, $e_b(t)$ is the error in the weight/buoyancy balance, $t$ is the time and $\tau$ is the variable of integration; it takes on values from time 0 to the present $t$. The gains, $K_p$, $K_i$ and $K_d$, are tuning parameters: $K_p$ deals with the present error, $K_i$ deals with the accumulation of past errors, and $K_d$ deals with a prediction of future errors.

The controller decides how to set the valves for filling or emptying the tanks based on the controller output, $u_b(t)$. If this output is positive, the AUV is negatively buoyant and water will be pumped out of the tanks by filled them with air to decrease the weight of the AUV. If the output is negative, the AUV is positively buoyant and water will be pumped into the tanks to increase the weight of the AUV. The proportional part of the controller will set the valve position proportion to the current error. The derivative action will add extra water in the tanks if the buoyancy is rising, and less when the buoyancy is falling. The integral action uses the average buoyancy in the past to detect whether the buoyancy is settling out too low or too high, and will then set the valve proportional to the past errors. However, the controller output, $u_b(t)$, is not directly used. As suggested in [9], the output will be fed through a saturation block that incorporates the limit on maximum change of buoyancy per control cycle.

```
e_prev = 0 %The previous error
intg = 0 %The integral variable

%The PID controller loop
while true

        %See Equation 9.8 for buoyancy error
        e_b = W + w - b;

        %Calculating the integral variable
        intg = intg + e_b*dt;

        %Calculating the derivative variable
        der = (e_b - e_prev)/dt;

        %Calculating the controller output
        u_b = K_p*e_b + K_i*intg + K_d*der;

        %Set the new previous error
        e_prev = e_b;

        %Wait for a dt step of time for next cycle
        wait(dt);

end
```

The implementation of this buoyancy controller will have to deal the following challenges that will affect its efficiency, according to [9]:

1. losses in different parts of the ballast assembly like the valves and pumps
2. rounding errors and resolution errors in connected with sensor readings
3. operation delays as the dynamics of the valves and pumps are not instantaneous

Challenge no. 2 is partly dealt with in the deadband. In the deadband block very small deviations in the error signal, $e_b(t)$, are ignored. Challenge no. 3 is why the wait-function is added in the code example. The ballast adjustment mechanism are not able to instantaneously change the buoyancy according to the control output, $u_b(t)$, therefore, a delay is added in the control loop to give it time to make the adjustment or at least begin the adjustment before the controller calculates a new output.

### 8.3.3 A pitch and roll controller

In addition to the buoyancy controller presented in Section 8.3.2, pitch and roll controllers could improve the performance and behaviour of the AUV. Pitch and roll controllers can ensure that the AUV has the correct pitch and roll angle during the whole mission. They can also be used actively during diving and surfacing to tilt the AUV downwards and upwards to help conserving energy. But, the pitch and roll controllers cannot use the thrusters and rudders to adjust the angles of the AUV. This is because the depth controller and the guidance controller use the thrusters and rudders to achieve the desired depth and trajectory. It is therefore important that the pitch and roll controllers do not use the thrusters and rudders as the different control systems have competing objectives. The pitch and roll controllers have to use other mechanisms to achieve their adjustments.

Adjustment of pitch and roll can, as presented in Section 2.7.2 and according to [14], be achieved with trim tanks or a weight shifting mechanism, both these methods works by shifting the CG of AUV. By using the trim tanks the pitch and roll controllers will shift the weight of the vehicle by modifying the water and air content in the tanks to comply with the objectives of the pitch and roll controllers [9]. A trim tank assembly include two tanks mounted inside the hull, water valves and pump, air valves and a compressed air cylinder. For pitch control, the vehicle has to be fitted with two tanks, one in the fore and one in the aft, which will make the pitch controller able to:

- shift the CG by decreasing the water content of one tank and increasing the water content of the other tank
- change the overall weight/buoyancy balance by decreasing or increasing the water content in both the tanks at the same rate (see Section 8.3.2)

With the trim tank assembly, a fore and aft tank, the x-coordinate of the CG of the vehicle will according to [18] be:

$$x_{CG} = \frac{1}{M}(m_{AUV}x_{AUV} + m_{fore}x_{fore} + m_{aft}x_{aft}) \tag{8.11}$$

Where $M$ is the total weight of the AUV and the tanks, $m_{AUV}$ is the weight of the AUV, $x_{AUV}$ is the initial x-coordinate of the AUV's CG, the $m_{fore}$ and $m_{aft}$ are the weight in the fore and aft tanks, and the $x_{fore}$ and $x_{aft}$ are x-coordinate of the CG of the fore and aft tank.

The CG can also be shifted by exploiting the payloads in the mid-section. If one of the heavier payloads is mounted on a rail at which the payload can be moved along, the CG could be shifted by moving the payload. This can be done for both the x- and y-axis. For the HUGIN 1000, the author suggests the use the two hard ballast tanks from the buoyancy controller in Section 8.3.2 as trim tanks for the pitch controller, while a weight shifting mechanism should be installed for the roll controller.

The error signals, $e_p(t)$ and $e_r(t)$, of the pitch and roll controllers can be defined as:

$$e_p(t) = p_{ref} - p(t) \tag{8.12}$$

$$e_r(t) = r_{ref} - r(t) \tag{8.13}$$

Where $p_{ref}$ and $r_{ref}$ are the set point pitch and roll, which are the desired pitch and roll angles, while $p(t)$ and $r(t)$ are the feedback pitch and roll, which are the actual pitch and roll that are fed back from the sensors to the controllers.

The pitch and roll controllers should be implemented as two independent controllers, each of which moves the CG independently along the x- and y-axis respectively, thus altering the pitch and roll. Figure 8.4 illustrates a possible PID controller for pitch. By designing the pitch and roll controllers as PID controllers the outputs, $u_p(t)$ and $u_r(t)$, will be:

$$\mathrm{u_p}(t) = K_p e_p(t) + K_i \int_0^t e_p(\tau)\, d\tau + K_d \frac{d}{dt} e_p(t) \tag{8.14}$$

$$\mathrm{u_r}(t) = K_p e_r(t) + K_i \int_0^t e_r(\tau)\, d\tau + K_d \frac{d}{dt} e_r(t) \tag{8.15}$$

The pitch and roll controllers will run every control cycle, adjusting the CG to maintain a zero-degree pitch and roll. However, the ballast is only adjusted if the pitch and roll error is outside their deadband. If the pitch and roll errors are within their deadbands then no action is taken by the controllers [9]. The software should then set a delay for the next control action calculation. This delay serves as an energy conservation technique [9]; if the current CG is achieving acceptable results, then the system should not do anything. However, if the pitch and roll errors are outside the deadband, then the PID controller will calculate a suitable adjustment. The output of the PIDs are fed through saturation blocks that incorporates the limited maximum change in CG's position per control cycle. These values are then fed to the adjustment mechanisms.

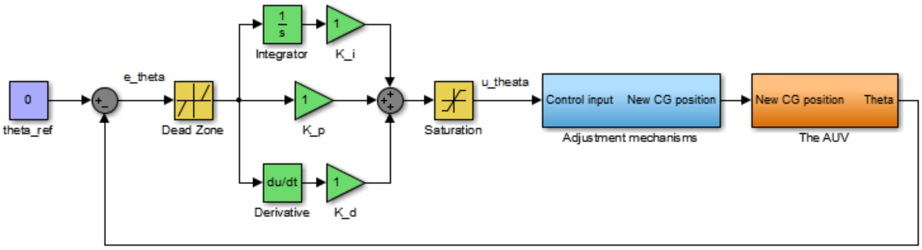


Figure 8.4: The PID pitch controller, where the PID roll controller will be similar

# Part IV

# CONCLUSION AND FURTHER WORK

# Chapter 9

# Concluding remarks

The objective of this Master Thesis was to develop a system for identification and adjustment of ballast errors in AUVs. The development and implementation of such a system can be justified by AUVs' requirement for correct ballast. An AUV with ballast errors will use an unnecessary amount of power and might have difficulty conducting its missions. Such problems will reduce the AUVs performance, and might make them impractical and less useful compared to ROVs. Today, Kongsberg Maritime and their customers spend a lot of time manually ballasting their AUVs to avoid these problems. It would therefore be beneficial to have a system that quickly and easily maps the necessary adjustments needed to gain a correct ballast. That is why Kongsberg Maritime commissioned this Master Thesis.

The conclusion in this Master Thesis is that a functioning system for identification and adjustments of ballast errors in AUVs has been developed and implemented (see Chapters 4 and 5). This system will aim to give AUVs a stable equilibrium with neutral buoyancy, which has been defined as the correct ballasting (see Section 2.7.1). The system will first identify any current ballast errors, based on manually entered measurements or collected mission data from the AUV. When ballast errors have been identified, the system will determine suitable ballast adjustments with one of the two specially designed methods; a CG shifting approach and a "slow control loop" approach.

The implemented system forms a static ballasting system since it does not run in real-time, as requested by Kongsberg Maritime. The system maps the required ballast adjustment for a human operator who has to perform the actual adjustment by adding or removing weights on the AUV before a mission. This makes the system only semi-automatic. Nonetheless, it will be faster and easier than the manual process that Kongsberg Maritime uses today, which takes time and requires experienced operators to get a decent ballast.

During the work with the Master Thesis, testing on the system was performed (see Chapter 6). The results showed that the system works according to the requirements of Kongsberg Maritime and its specification (see Chapter 7 and Section 5.1). The tests showed that the system would as far as possible map ballast adjustments that will counteract any ballast errors. However, it is almost impossible to achieve the optimal calculated adjustments with the number of different weight sizes that are available for adjustment. This reduces the performance of the system. A possible solution has been presented in Section 8.1, which involves acquiring a new weight that is not proportional to the other weights.

In addition to the development and implementation of the system commissioned by Kongsberg Maritime, solutions that will make this system more general, more efficient and fully-automatic have been researched. The implemented system uses very specialized methods to determine the suitable ballast adjustments based on identified ballast errors and might need several missions to gain an optimal ballast configuration. In Section 8.2 solutions that will make the system more general and efficient have been discussed. In these solutions the correction of ballast errors are formulated as optimization problems. These solutions will not make the system fully-automatic nor will they run in real-time. However, they would use fewer missions to find an optimal ballast adjustment, which makes them more efficient. There are, however, challenges involved in using these solutions. They require a measurement of the CG and an algorithm that can handle integer linear programming problems.

Both the implemented system and the optimization solutions are only semi-automatic and do not run in real-time. However, fully-automatic and real-time systems for identification and correction of ballast errors exists. In Section 8.3 some active ballasting systems have been discussed. Possible fully-automatic and real-time running solutions for Kongsberg Maritime's HUGIN 1000 have been presented. Lastly, in the further work (see Section 10), additional aspects that should be considered following this Master Thesis are presented.

# Chapter 10

# Further work

Further work on the system developed and implemented in this Master Thesis would include several aspects. First, more testing should be carried out. The tests done in this Master Thesis prove that the system works, however, it should also be tested by using a simulator that could show how the AUV will behave with the ballast adjustment. This simulator should include a model of an AUV that can give all the outputs needed for the ballasting system; depth, propeller speed, velocity, pitch, roll, temperature and salinity. By studying the response of ballast adjustments in this model, the size of the weight adjustments in the pre mission mode can be modified to gain an optimal ballast adjustment with fewer loops of the pre and post mission mode.

It should be considered whether it would be beneficial to install an instrument for CG measurement. If the CG is known, one of the optimization solutions discussed in Section 8.2 can be implemented. The optimization approach in Section 8.2 should be tested to see if it yields better solutions than the two different solutions for determining the ballast adjustment the implemented system.

The system implemented in this Master Thesis is a static ballast system that does not ran in real time, as Kongsberg Maritime wanted. Nevertheless, systems that run in real-time do exist and are in many aspects beneficial, especially concerning energy consumption. Therefore, an active ballasting system should be considered. Some possible active ballasting systems are presented in Section 8.3. However, there are little space left in the Kongsberg Maritime's AUVs for an active ballasting assembly. One solution is to produce new vehicle sections with the active ballast assembly.

In respect to actual installing a finished and approved system on a physical AUV, the system should be implemented in a C language, which is the Kongsberg Maritime's preferred language for their systems on AUVs (see Section 4.1).

# Chapter 11

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# Part V

# APPENDICES

# Appendix A

# HUGIN 1000's volume

The volume of the AUV is an essential parameter when calculating the buoyancy force acting on it. However, Kongsberg Maritime did not specify the volume of the HUGIN 1000. Thus, the volume had be calculated. It was calculated by using Newton's second law:

$$\sum(\mathbf{F}) = W - B = 0 \tag{A.1}$$

The volume can be derived by using the known difference between the AUV's weight in air and water compared to the buoyancy force:

$$\begin{aligned}(W_{air} - W_{water}) - B &= 0 \\ (m_{air}g - m_{water}g) - \rho g \nabla &= 0 \qquad \text{(A.2)}\end{aligned}$$

An expression for the volume of water being pushed away, $\nabla$, is obtained by rearranging Equation A.2:

$$\nabla = \frac{1}{\rho}(m_{air} - m_{water}) \tag{A.3}$$

This volume of water, $\nabla$, corresponds to the volume of the AUV, V, since the AUV is fully submerged:

$$\nabla = V \tag{A.4}$$

By using the measurements in Table 3.1, the volume of the HUGIN 1000 is calculated to be:

$$V = \frac{1498\ \mathrm{kg} - (-65\ \mathrm{kg})}{1024.8\ \mathrm{kg/m^3}} = 1.5252\ \mathrm{m^3}$$

# Appendix B

# Temperature check algorithm

The algorithm used for date checking and temperature setting, which was discussed in Section 5.5.3, is shown underneath.

```
%The time period between missions is equal or less than a month
if dateNow-dateThen >= 1 month

        %The operator wants to use the last measured temperature
        if newTempertureSelection == No

                %The temperature is set to the last measured temperature
                temperature = lastTemperature;

        %The operator wants to enter a new temperature
        elseif newTempertureSelection == Yes

                %A new value is entered for the temperature
                temperature = newTemperature;

        end

%The time period between missions is more than a month
else

        %A new value is entered for the temperature
        temperature = newTemperature;

end
```

# Appendix C

# Water density

## C.1 Water density graph

Figure C.1, courtesy of [6], was used to check the water density calculator implemented based on [7] as mentioned in Section 4.5.

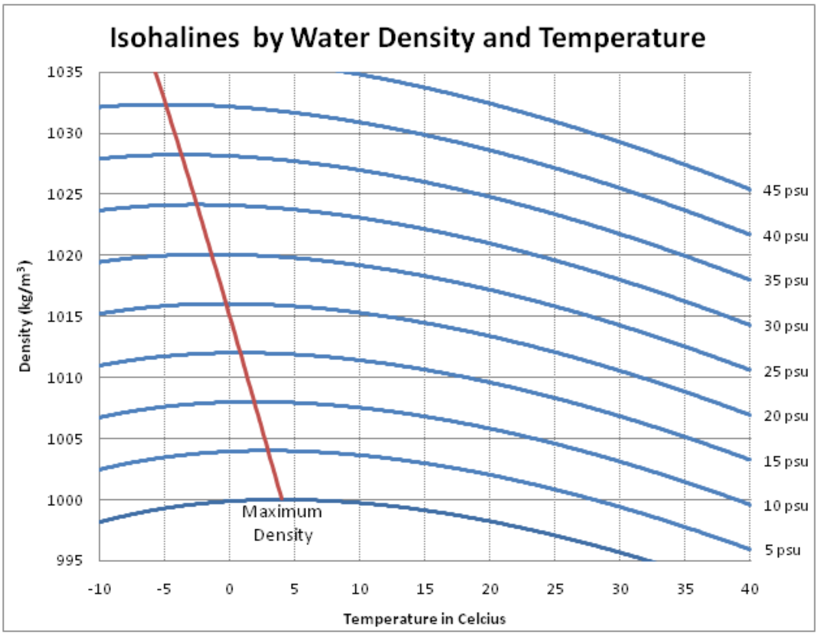


Figure C.1: Plot of water density relative to salinity and temperature, courtesy of [6]

## C.2 Calculated water density values

Table C.1 shows the calculated water density at 4 degrees Celsius and a salinity of 35 000 ppm. To calculate these values the water density calculator at [4] and `http://www.calctool.org/CALC/other/games/depth_press` was used.

| | |
|---|---|
| without pressure included into the calculation | 1027.812$kg/m^3$ |
| with pressure at 0 meters depth | 1027.834$kg/m^3$ |
| with pressure at 10 meters depth | 1027.880$kg/m^3$ |
| with pressure at 100 meters depth | 1028.301$kg/m^3$ |
| with pressure at 1000 meters depth | 1032.463$kg/m^3$ |

Table C.1: The calculated water density at 4 degrees Celsius and a salinity of 35 000 ppm

## C.3 Water density calculator code

This implementation of a water density calculator was based on [7] and used as explained in Section 4.5 to calculate the water density. By viewing the page source code of [7], the HTML was converted to Matlab code and modified to fit the input used in the system developed in this Master Thesis.

```matlab
%This function calculates the water density based on only temperature and salinity. The calculation are borrowed from web page http://www.csgnetwork.com/h2odenscalc.html, which has based its calculations on Millero, F, C. Chen, A Bradshaw, and K. Schleicher, 1980: "A new high pressure equation of state for seawater", Deep Sea Research, Part A, 27, pages 255-264.

%Density based on temperature
density_temp = 1000*(1.0-(temperature+288.9414)/(508929.2...
          (temperature+68.12963))*((temperature-3.9863)^2));

%Density based on temperature and salinity
A = 0.824493-0.0040899*temperature+0.000076438...
          *temperature^2-0.00000082467*temperature^3...
          +0.0000000053675 temperature^4;
B = -0.005724+0.00010227*temperature...
          -0.0000016546*temperature^2;
density = density_temp+A*salinity+B*salinity^(3/2)...
          +0.00048314*salinity^2;
```

# Appendix D

# Algorithms for detection of ballast errors

## D.1 Algorithm code for depth comparison check

The algorithm derived for identifying depth error, see Section 5.3.1, was implemented with the Matlab code shown below.

```
%Picking out the middle section of the data
first = round(0.4 length(commandDepthData));
last = round(0.6 length(commandDepthData));

%Array for storing check values for depth
depthCheck = zeros(length(commandDepthData),1);

%While loop for checking depth deviation
i = 2; %Index for loop
while i <= length(depthCheck)

        %Checking for steps in commanded depth
        if commandDepthData(i) == commandDepthData(i-1)

                %Subtracting measured depth from commanded depth
                depthCheck(i) = commandDepthData(i)-measureDepthData
                    (i);
                i = i+1; %Loop incrementing

        %Checking the size of the step
        elseif abs(commandDepthData(i)-commandDepthData(i-1)) < 30

                %Marking array with data that wouldn't be used
                depthCheck(i) = NaN;
                i = i+300; %Skipping multiple iterations

        elseif abs(commandDepthData(i)-commandDepthData(i-1)) < 50

                depthCheck(i) = NaN;
                i = i+400; %Skipping multiple iterations

        elseif abs(commandDepthData(i)-commandDepthData(i-1)) < 100
                depthCheck(i) = NaN;
```

```
                i = i+500; %Skipping multiple iterations

        else
                depthCheck(i) = NaN;
                i = i+600; %Skipping multiple iterations
        end

end

%Removing NaNs from array
depthCheck(isnan(depthCheck)) = [];

%Removing the zeros outside the used section of used data
buoyancyCheck = depthCheck(first:last);

%Calculating the average depth deviation
avgBuoyDer = sum(buoyancyCheck)/length(buoyancyCheck);
```

## D.2 Algorithm code for pitch comparison check

The algorithm derived for identifying pitch error, based on comparison of measured and commanded pitch, see Section 5.3.2, was implemented with the Matlab code shown below.

```
%Picking out the middle section of the data
first = round(0.4 length(measuredPitchData));
last = round(0.6 length(measuredPitchData));

%Array for storing check values for pitch
pitchMeasComCheck_temp = zeros(length(measuredPitchData),1);

%While loop for checking pitch deviation based on comparison
i = 3; %Index for loop
while i <= length(measuredPitchData)

        %Subtracting commanded pitch from measured pitch
        pitchMeasComCheck_temp(i) = measuredPitchData(i)-
            commandedPitchData(i);

        %Loop incrementing
        i = i+1;
end

%Removing the zeros outside the used section of used data
pitchMeasComCheck = pitchMeasComCheck_temp(first:last);

%Removing NaNs from array
pitchMeasComCheck(isnan(pitchMeasComCheck)) = [];
```

```

%Calculating the average pitch deviation
avgPitchComDer = sum(pitchMeasComCheck)/length(pitchMeasComCheck);
```

## D.3 Algorithm code for pitch depth check

The algorithm derived for identifying pitch error, based on a check of depth, see Section 5.3.2, was implemented with the Matlab code shown below.

```
%Picking out the middle section of the data
first = round(0.4 length(measuredPitchData));
last = round(0.6 length(measuredPitchData));

%Array for storing check values for pitch
pitchDepthCheck_temp = zeros(length(measuredPitchData),1);

%While loop for checking pitch deviation based on depth data
i = 3; %Index for loop
while i <= length(measuredPitchData)

        %Checking for stable depth samples (der_depth == 0)
        if measuredDepthData(i) == measuredDepthData(i-1) && measuredDepthData(i-1) == measuredDepthData(i-2)

                %Adding pitch values to array for stable depth samples
                pitchDepthCheck_temp(i) = measuredPitchData(i);

        else
                pitchDepthCheck_temp(i) = NaN;
        end

        %Loop incrementing
        i = i+1;

end

%Removing the zeros outside the used section of used data
pitchDepthCheck = pitchDepthCheck_temp(first:last);

%Removing NaNs from array
pitchDepthCheck(isnan(pitchDepthCheck)) = [];

%Calculating the average pitch deviation
avgPitchDepthDer = sum(pitchDepthCheck)/length(pitchDepthCheck);
```

## D.4 Algorithm code for roll checking

The algorithm derived for identifying roll error, see Section 5.3.3, was implemented with the Matlab code shown below.

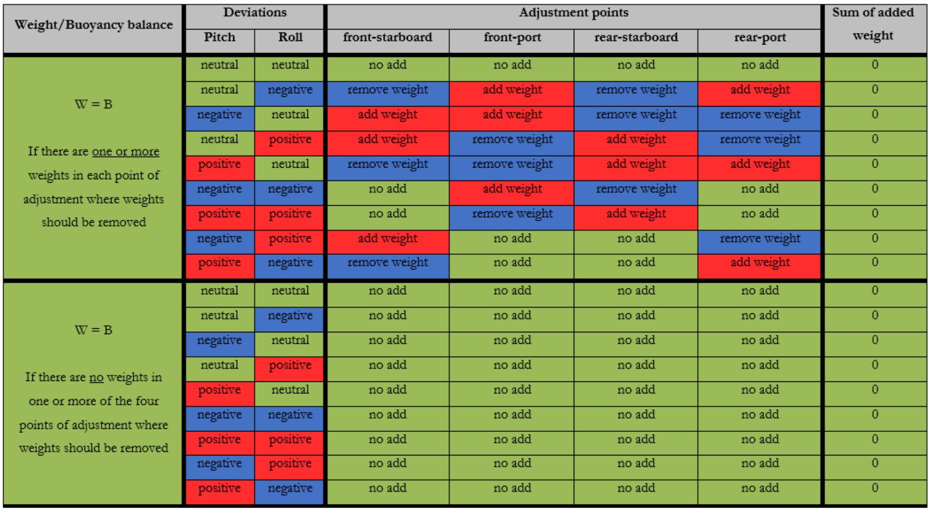
```matlab
%Array for storing roll values
rollCheck = zeros(length(rollData),1);

%While loop for checking roll deviation based on propeller speed and forward velocity
i = 1; %Index for loop
while i <= length(rollCheck)

        %Checking a propeller speed of 160 rpm
        if revolutionsData(i) == 160

                %Checking a velocity of about 2 m/s
                if velocityData(i) > 1.995 && velocityData(i) < 2.005

                        %Adding roll values to array
                        rollCheck(i) = rollData(i);

                else
                        rollCheck(i) = NaN;
                end

        else
                rollCheck(i) = NaN;
        end

        %Loop incrementing
        i = i+1;

end

%Removing NaNs from array
rollCheck(isnan(rollCheck)) = [];

%Calculating the average roll deviation
avgRollDer = sum(rollCheck)/length(rollCheck)
```

# Appendix E

# Table for adjustment in the pre mission mode

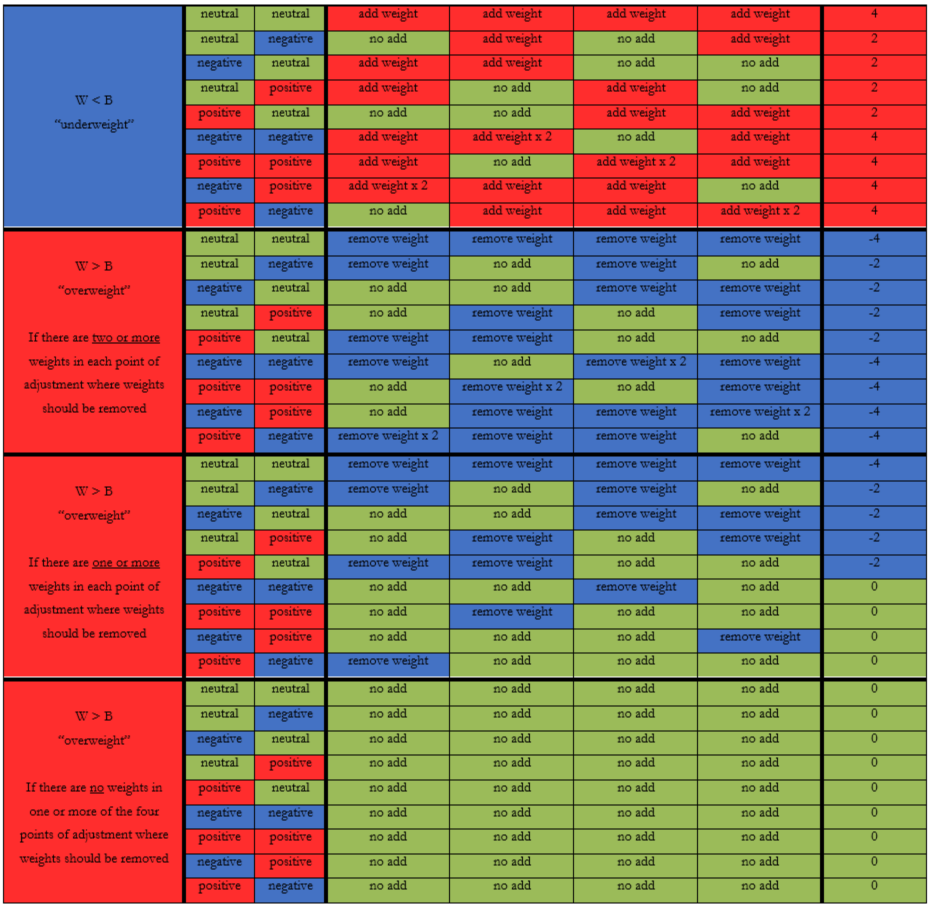
## E.1 Illustrating table for adjustment in the pre mission mode

The figures below illustrates the determination of ballast adjustments in the pre mission mode (see Section 5.4.2).



| Weight/Buoyancy balance | Deviations | | Adjustment points | | | | Sum of added weight |
|---|---|---|---|---|---|---|---|
| | Pitch | Roll | front-starboard | front-port | rear-starboard | rear-port | |
| W = B<br>If there are one or more weights in each point of adjustment where weights should be removed | neutral | neutral | no add | no add | no add | no add | 0 |
| | neutral | negative | remove weight | add weight | remove weight | add weight | 0 |
| | negative | neutral | add weight | add weight | remove weight | remove weight | 0 |
| | neutral | positive | add weight | remove weight | add weight | remove weight | 0 |
| | positive | neutral | remove weight | remove weight | add weight | add weight | 0 |
| | negative | negative | no add | add weight | remove weight | no add | 0 |
| | positive | positive | no add | remove weight | add weight | no add | 0 |
| | negative | positive | add weight | no add | no add | remove weight | 0 |
| | positive | negative | remove weight | no add | no add | add weight | 0 |
| W = B<br>If there are no weights in one or more of the four points of adjustment where weights should be removed | neutral | neutral | no add | no add | no add | no add | 0 |
| | neutral | negative | no add | no add | no add | no add | 0 |
| | negative | neutral | no add | no add | no add | no add | 0 |
| | neutral | positive | no add | no add | no add | no add | 0 |
| | positive | neutral | no add | no add | no add | no add | 0 |
| | negative | negative | no add | no add | no add | no add | 0 |
| | positive | positive | no add | no add | no add | no add | 0 |
| | negative | positive | no add | no add | no add | no add | 0 |
| | positive | negative | no add | no add | no add | no add | 0 |

Figure E.1: Mapping of ballast adjustment based on pitch and roll in the pre mission mode (part 1 of the table)



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| W < B<br>“underweight” | neutral | neutral | add weight | add weight | add weight | add weight | 4 |
| | neutral | negative | no add | add weight | no add | add weight | 2 |
| | negative | neutral | add weight | add weight | no add | no add | 2 |
| | neutral | positive | add weight | no add | add weight | no add | 2 |
| | positive | neutral | no add | no add | add weight | add weight | 2 |
| | negative | negative | add weight | add weight x 2 | no add | add weight | 4 |
| | positive | positive | add weight | no add | add weight x 2 | add weight | 4 |
| | negative | positive | add weight x 2 | add weight | add weight | no add | 4 |
| | positive | negative | no add | add weight | add weight | add weight x 2 | 4 |
| W > B<br>“overweight”<br>If there are two or more weights in each point of adjustment where weights should be removed | neutral | neutral | remove weight | remove weight | remove weight | remove weight | -4 |
| | neutral | negative | remove weight | no add | remove weight | no add | -2 |
| | negative | neutral | no add | no add | remove weight | remove weight | -2 |
| | neutral | positive | no add | remove weight | no add | remove weight | -2 |
| | positive | neutral | remove weight | remove weight | no add | no add | -2 |
| | negative | negative | remove weight | no add | remove weight x 2 | remove weight | -4 |
| | positive | positive | no add | remove weight x 2 | no add | remove weight | -4 |
| | negative | positive | no add | remove weight | remove weight | remove weight x 2 | -4 |
| | positive | negative | remove weight x 2 | remove weight | remove weight | no add | -4 |
| W > B<br>“overweight”<br>If there are one or more weights in each point of adjustment where weights should be removed | neutral | neutral | remove weight | remove weight | remove weight | remove weight | -4 |
| | neutral | negative | remove weight | no add | remove weight | no add | -2 |
| | negative | neutral | no add | no add | remove weight | remove weight | -2 |
| | neutral | positive | no add | remove weight | no add | remove weight | -2 |
| | positive | neutral | remove weight | remove weight | no add | no add | -2 |
| | negative | negative | no add | no add | remove weight | no add | 0 |
| | positive | positive | no add | remove weight | no add | no add | 0 |
| | negative | positive | no add | no add | no add | remove weight | 0 |
| | positive | negative | remove weight | no add | no add | no add | 0 |
| W > B<br>“overweight”<br>If there are no weights in one or more of the four points of adjustment where weights should be removed | neutral | neutral | no add | no add | no add | no add | 0 |
| | neutral | negative | no add | no add | no add | no add | 0 |
| | negative | neutral | no add | no add | no add | no add | 0 |
| | neutral | positive | no add | no add | no add | no add | 0 |
| | positive | neutral | no add | no add | no add | no add | 0 |
| | negative | negative | no add | no add | no add | no add | 0 |
| | positive | positive | no add | no add | no add | no add | 0 |
| | negative | positive | no add | no add | no add | no add | 0 |
| | positive | negative | no add | no add | no add | no add | 0 |

Figure E.2: Mapping of ballast adjustment based on pitch and roll in the pre mission mode (part 2 of the table)

## E.2 Algorithm code for adjustment in the pre mission mode

The algorithm derived for the ballast adjustments in Figures E.1 and E.2 was implemented with the Matlab code shown below.

```
function [calcultedAdjustment] = weightAdjustmentController(
    addedWeight,...
    w_small,weightDev,depthDev,pitchDev,rollDev,depthError,...
    buoyancyError,pitchError,rollError,x_aw)
%weightAdjustmentController is a function that determines a suitable
     weight
%adjustment based on weights already used, the depth,
%weight/buoyancy balance, the pitch and roll deviations

    %The already added weights
    m_1 = addedWeight(1);
    m_2 = addedWeight(2);
    m_3 = addedWeight(3);
    m_4 = addedWeight(4);

    %Postion of point of adjustment
    x_5 = x_aw(1);
    x_7 = x_aw(3);

    %Calculating the new adjustment
     if depthError <= depthDev(1) && depthError >= depthDev(2)
        %Depth error within the deviation limits
        w_adjust = w_small;

        if abs(pitchError) < pitchDev && abs(rollError) < rollDev
            m_5 = m_1;
            m_6 = m_2;
            m_7 = m_3;
            m_8 = m_4;
        elseif abs(pitchError) < pitchDev && rollError < -rollDev
            if m_1 >= w_small && m_3 >= w_small
                m_5 = m_1 - w_adjust;
                m_6 = m_2 + w_adjust;
                m_7 = m_3 - w_adjust;
                m_8 = m_4 + w_adjust;
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        elseif pitchError < -pitchDev && abs(rollError) < rollDev
            if m_3 >= w_small && m_4 >= w_small
```

```
                m_5 = m_1 + w_adjust;
                m_6 = m_2 + w_adjust;
                m_7 = m_3 - w_adjust;
                m_8 = m_4 - w_adjust;
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        elseif abs(pitchError) < pitchDev && rollError > rollDev
            if m_2 >= w_small && m_4 >= w_small
                m_5 = m_1 + w_adjust;
                m_6 = m_2 - w_adjust;
                m_7 = m_3 + w_adjust;
                m_8 = m_4 - w_adjust;
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        elseif pitchError > pitchDev && abs(rollError) < rollDev
            if m_1 >= w_small && m_2 >= w_small
                m_5 = m_1 - w_adjust;
                m_6 = m_2 - w_adjust;
                m_7 = m_3 + w_adjust;
                m_8 = m_4 + w_adjust;
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        elseif pitchError < -pitchDev && rollError < -rollDev
            if m_3 >= w_small
                m_5 = m_1;
                m_6 = m_2 + w_adjust;
                m_7 = m_3 - w_adjust;
                m_8 = m_4;
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        elseif pitchError > pitchDev && rollError > rollDev
            if m_2 >= w_small
                m_5 = m_1;
                m_6 = m_2 - w_adjust;
                m_7 = m_3 + w_adjust;
                m_8 = m_4;
```

```
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        elseif pitchError < -pitchDev && rollError > rollDev
            if m_4 >= w_small
                m_5 = m_1 + w_adjust;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4 - w_adjust;
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        elseif pitchError > pitchDev && rollError < -rollDev
            if m_1 >= w_small
                m_5 = m_1 - w_adjust;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4 + w_adjust;
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        end

    elseif depthError < depthDev(1)
        %According the the depth deviation the vehicle is too light
        if buoyancyError > weightDev(1)
            m_dif = (buoyancyError/4)-(4*w_small);
            m_f = ((abs(x_7)/abs(x_5)+abs(x_7))*m_dif);
            m_a = ((abs(x_5)/abs(x_5)+abs(x_7))*m_dif);
            w_1 = m_f/2;
            w_2 = m_f/2;
            w_3 = m_a/2;
            w_4 = m_a/2;
            w_adjust = w_small;
        else
            w_1 = 0;
            w_2 = 0;
            w_3 = 0;
            w_4 = 0;
            w_adjust = w_small;
        end

        if abs(pitchError) < pitchDev && abs(rollError) < rollDev
```

```
            m_5 = m_1 + w_1 + w_adjust;
            m_6 = m_2 + w_2 + w_adjust;
            m_7 = m_3 + w_3 + w_adjust;
            m_8 = m_4 + w_4 + w_adjust;
        elseif abs(pitchError) < pitchDev && rollError < -rollDev
            m_5 = m_1 + w_1;
            m_6 = m_2 + w_2 + w_adjust;
            m_7 = m_3 + w_3;
            m_8 = m_4 + w_4 + w_adjust;
        elseif pitchError < -pitchDev && abs(rollError) < rollDev
            m_5 = m_1 + w_1 + w_adjust;
            m_6 = m_2 + w_2 + w_adjust;
            m_7 = m_3 + w_3;
            m_8 = m_4 + w_4;
        elseif abs(pitchError) < pitchDev && rollError > rollDev
            m_5 = m_1 + w_1 + w_adjust;
            m_6 = m_2 + w_2;
            m_7 = m_3 + w_3 + w_adjust;
            m_8 = m_4 + w_4;
        elseif pitchError > pitchDev && abs(rollError) < rollDev
            m_5 = m_1 + w_1;
            m_6 = m_2 + w_2;
            m_7 = m_3 + w_3 + w_adjust;
            m_8 = m_4 + w_4 + w_adjust;
        elseif pitchError < -pitchDev && rollError < -rollDev
            m_5 = m_1 + w_1 + w_adjust;
            m_6 = m_2 + w_2 + (2*w_adjust);
            m_7 = m_3 + w_3;
            m_8 = m_4 + w_4 + w_adjust;
        elseif pitchError > pitchDev && rollError > rollDev
            m_5 = m_1 + w_1 + w_adjust;
            m_6 = m_2 + w_2;
            m_7 = m_3 + w_3 + (2*w_adjust);
            m_8 = m_4 + w_4 + w_adjust;
        elseif pitchError < -pitchDev && rollError > rollDev
            m_5 = m_1 + w_1 + (2*w_adjust);
            m_6 = m_2 + w_2 + w_adjust;
            m_7 = m_3 + w_3 + w_adjust;
            m_8 = m_4 + w_4;
        elseif pitchError > pitchDev && rollError < -rollDev
            m_5 = m_1 + w_1;
            m_6 = m_2 + w_2 + w_adjust;
            m_7 = m_3 + w_3 + w_adjust;
            m_8 = m_4 + w_4 + (2*w_adjust);
        end

    elseif depthError > depthDev(2)
        %According the the depth deviation the vehicle is too heavy
        if buoyancyError < -weightDev(1)
            m_dif = abs((abs(buoyancyError)/4)-(4*w_small));
            m_f = ((abs(x_7))/(abs(x_5)+abs(x_7)))*m_dif;
            m_a = ((abs(x_5))/(abs(x_5)+abs(x_7)))*m_dif;
```

```
            w_1 = m_f/2;
            w_2 = m_f/2;
            w_3 = m_a/2;
            w_4 = m_a/2;
            w_adjust = w_small;
        else
            w_1 = 0;
            w_2 = 0;
            w_3 = 0;
            w_4 = 0;
            w_adjust = w_small;
        end

        if abs(pitchError) < pitchDev && abs(rollError) < rollDev
            if m_1 >= w_small && m_2 >= w_small && m_3 >= w_small
                ...
                    && m_4 >= w_small
                m_5 = m_1 - w_1 - w_adjust;
                m_6 = m_2 - w_2 - w_adjust;
                m_7 = m_3 - w_3 - w_adjust;
                m_8 = m_4 - w_4 - w_adjust;
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        elseif abs(pitchError) < pitchDev && rollError < -rollDev
            if m_1 >= w_small && m_3 >= w_small
                m_5 = m_1 - w_1 - w_adjust;
                m_6 = m_2 - w_2;
                m_7 = m_3 - w_3 - w_adjust;
                m_8 = m_4 - w_4;
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        elseif pitchError < -pitchDev && abs(rollError) < rollDev
            if m_3 >= w_small && m_4 >= w_small
                m_5 = m_1 - w_1;
                m_6 = m_2 - w_2;
                m_7 = m_3 - w_3 - w_adjust;
                m_8 = m_4 - w_4 - w_adjust;
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        elseif abs(pitchError) < pitchDev && rollError > rollDev
```

```
        if m_2 >= w_small && m_4 >= w_small
            m_5 = m_1 - w_1;
            m_6 = m_2 - w_2 - w_adjust;
            m_7 = m_3 - w_3;
            m_8 = m_4 - w_4 - w_adjust;
        else
            m_5 = m_1;
            m_6 = m_2;
            m_7 = m_3;
            m_8 = m_4;
        end
    elseif pitchError > pitchDev && abs(rollError) < rollDev
        if m_1 >= w_small && m_2 >= w_small
            m_5 = m_1 - w_1 - w_adjust;
            m_6 = m_2 - w_2 - w_adjust;
            m_7 = m_3 - w_3;
            m_8 = m_4 - w_4;
        else
            m_5 = m_1;
            m_6 = m_2;
            m_7 = m_3;
            m_8 = m_4;
        end
    elseif pitchError < -pitchDev && rollError < -rollDev
        if m_1 >= w_small && m_3 >= (2*w_small) && m_4 >= w_small
            m_5 = m_1 - w_1 - w_adjust;
            m_6 = m_2 - w_2;
            m_7 = m_3 - w_3 - (2*w_adjust);
            m_8 = m_4 - w_4 - w_adjust;
        elseif m_3 >= w_small
            m_5 = m_1 - w_1;
            m_6 = m_2 - w_2;
            m_7 = m_3 - w_3 - w_adjust;
            m_8 = m_4 - w_4;
        else
            m_5 = m_1;
            m_6 = m_2;
            m_7 = m_3;
            m_8 = m_4;
        end
    elseif pitchError > pitchDev && rollError > rollDev
        if m_2 >= (2*w_small) && m_4 >= w_small
            m_5 = m_1 - w_1;
            m_6 = m_2 - w_2 - (2*w_adjust);
            m_7 = m_3 - w_3;
            m_8 = m_4 - w_4 - w_adjust;
        elseif m_2 >= w_small
            m_5 = m_1 - w_1;
            m_6 = m_2 - w_2 - w_adjust;
            m_7 = m_3 - w_3;
            m_8 = m_4 - w_4;
```

```
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        elseif pitchError < -pitchDev && rollError > rollDev
            if m_2 >= w_small && m_3 >= w_small && m_4 >= (2*w_small)
                m_5 = m_1 - w_1;
                m_6 = m_2 - w_2 - w_adjust;
                m_7 = m_3 - w_3 - w_adjust;
                m_8 = m_4 - w_4 - (2*w_adjust);
            elseif m_4 >= w_small
                m_5 = m_1 - w_1;
                m_6 = m_2 - w_2;
                m_7 = m_3 - w_3;
                m_8 = m_4 - w_4 - w_adjust;
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        elseif pitchError > pitchDev && rollError < -rollDev
            if m_1 >= (2*w_small) && m_2 >= w_small && m_3 >= w_small
                m_5 = m_1 - w_1 - (2*w_adjust);
                m_6 = m_2 - w_2 - w_adjust;
                m_7 = m_3 - w_3 - w_adjust;
                m_8 = m_4 - w_4;
            elseif m_1 >= w_small
                m_5 = m_1 - w_1 - w_adjust;
                m_6 = m_2 - w_2;
                m_7 = m_3 - w_3;
                m_8 = m_4 - w_4;
            else
                m_5 = m_1;
                m_6 = m_2;
                m_7 = m_3;
                m_8 = m_4;
            end
        end
    end

    calcultedAdjustment = [m_5 m_6 m_7 m_8];

end
```

# Appendix F

# Test cases for the system

## F.1 Test cases for the first mission mode

Different cases of inputs giving different ballast errors have been used to test the first mission mode. The cases are:

- Case 1: no ballast errors
- Case 2: only positive weight/buoyancy imbalance
- Case 3: positive weight/buoyancy imbalance and negative pitch error
- Case 4: positive weight/buoyancy imbalance and positive roll error
- Case 5a: positive weight/buoyancy imbalance and negative pitch and roll errors
- Case 5b: positive weight/buoyancy imbalance and positive pitch and roll errors

Table F.1 shows the weight distribution used to get the different test cases. The first column on each row is the total weight of the AUV, the second is weight in the fore/starboard, third is fore/port, fourth is aft/starboard and fifth is aft/port.

| Cases | Total | Fore/Star | Fore/Port | Aft/Star | Aft/Port |
|---|---|---|---|---|---|
| Case 1 | 1566.8 | 391.7 | 391.7 | 391.7 | 391.7 |
| Case 2 | 1498.0 | 374.5 | 374.5 | 374.5 | 374.5 |
| Case 3 | 1498.0 | 386.5 | 386.5 | 362.5 | 362.5 |
| Case 4 | 1498.0 | 378.5 | 370.5 | 378.5 | 370.5 |
| Case 5a | 1498.0 | 382.5 | 390.5 | 358.5 | 366.5 |
| Case 5b | 1498.0 | 366.5 | 358.5 | 390.5 | 382.5 |

Table F.1: The test cases for the first mission mode

## F.2 Test case for the post mission mode

The post mission mode will be tested with a set of mission data provided by Kongsberg Maritime (see Section 3.2), which are realistic mission data from an AUV that is not optimally ballasted; the AUV has errors in depth, pitch and roll. The plots in Figures F.1, F.2 and F.3 show the data on depth, pitch and roll.

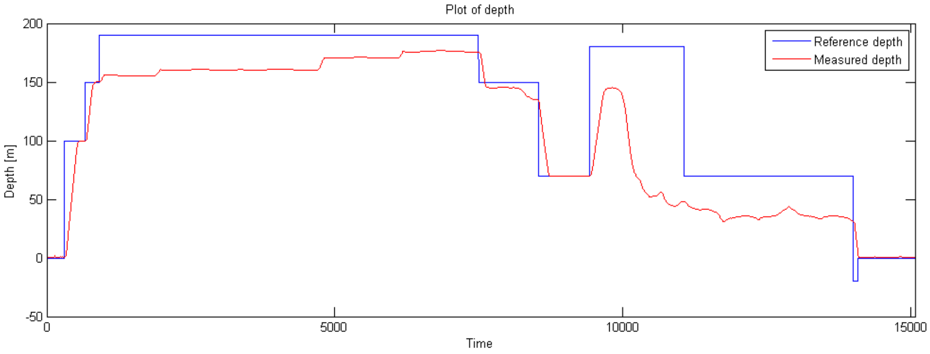


Figure F.1: Plot of the commanded and measured depth

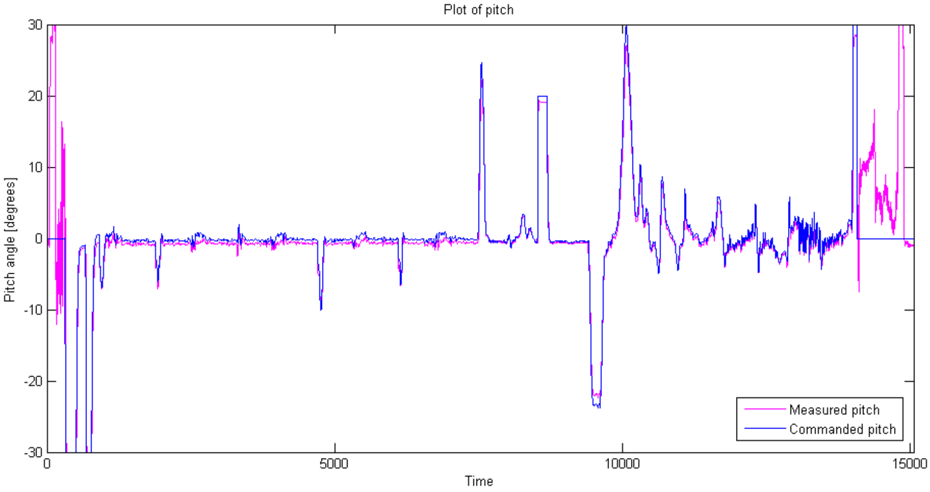


Figure F.2: Plot of the commanded and measured pitch

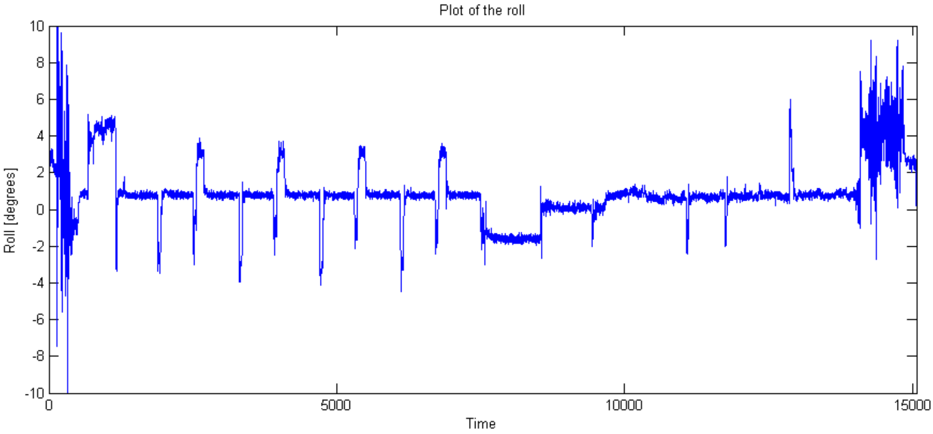


Figure F.3: Plot of the measured roll

It is assumed that the $2^{nd}$ test case from the first mission mode was the initial condition of the vehicle where the water temperature was set to 4 °C and the salinity to 35 ppt.

## F.3 Test cases for the pre mission mode

The test cases used for testing of the pre mission mode are slightly modified from the cases used for testing of the first mission mode to imitate errors that could have be identified by the post mission mode:

- Case 1: no ballast errors
- Case 2a: only positive depth error
- Case 2b: only negative depth error
- Case 3: only positive pitch error
- Case 4: only negative roll error
- Case 5: negative pitch error and positive roll error
- Case 6a: depth, pitch and roll errors, all positive deviations
- Case 6b: depth, pitch and roll errors, all negative deviations

- Case 6c: positive depth error, negative pitch and roll errors
- Case 6d: negative depth error, positive pitch and roll errors

Table F.2 shows the errors used to get the different test cases. The first column on each row is the depth error, the second is pitch error and third is the roll error.

| Cases | Depth | Pitch | Error |
|---|---|---|---|
| Case 1 | 0.0 | 0.0 | 0.0 |
| Case 2a | +0.5 | 0.0 | 0.0 |
| Case 2b | -0.5 | 0.0 | 0.0 |
| Case 3 | 0.0 | +0.8 | 0.0 |
| Case 4 | 0.0 | 0.0 | -0.3 |
| Case 5 | 0.0 | -0.8 | +0.3 |
| Case 6a | +0.5 | +0.8 | +0.3 |
| Case 6b | -0.5 | -0.8 | -0.3 |
| Case 6c | +0.5 | -0.8 | -0.3 |
| Case 6d | -0.5 | +0.8 | +0.3 |

Table F.2: The test cases for the pre mission mode

For all cases it is assumed that the $2^{nd}$ test case from the first mission mode was the initial condition of the vehicle, and it has therefore been added several weights to each point of adjustments so that weights can be removed from any point. The water temperature is set to about 6.54 °C and the salinity to 34.49 ppt based on the mission data.

## F.4 Test case for the whole system

In test of the whole system all the mission modes will be tested in a specific sequence; first, post and then pre mission mode. For the first mission mode an input case that give a positive weight/buoyancy imbalance, a negative pitch error and a positive roll error is entered. Then the post mission mode will be ran with the mission data provided by Kongsberg Maritime (see Section 3.2), which are realistic mission data from an AUV with a positive depth error, negative pitch error and positive roll just like for the first mission mode. The pre mission mode is ran with the ballast errors identified by the post mission mode. The used inputs for this whole system test are shown in Table F.3.

| | First mission | Post mission |
|---|---|---|
| Temperature | 4 | 6.545581 |
| Salinity | 35 | 34.49 |
| Total weight | 1498.0 | * |
| Fore/Star | 404.5 | * |
| Fore/Port | 384.5 | * |
| Aft/Star | 364.5 | * |
| Aft/Port | 344.5 | * |
| Depth error | Unknown | 8.7594 |
| Pitch error | Unknown | -0.59959 |
| Roll error | Unknown | 0.73636 |

Table F.3: The test cases for the testing of the whole system

*) Depending on the weight adjustment from the first mission mode.

# Appendix G

# Results of the test cases

## G.1 Test results for the first mission mode

All the tests performed on the first mission mode were done in accordance with the test routine presented in Section 6.1. The resulting calculated ballast adjustments for the test cases are listed in Table G.1, where the first column represents how much weight should be added in total, while the other columns represents how much weight should be added to each point of adjustment.

| Cases | Total | Fore/Star | Fore/Port | Aft/Star | Aft/Port |
|---|---|---|---|---|---|
| Case 1 | 0.8 | 0.1 | 0.1 | 0.3 | 0.3 |
| Case 2 | 69.8 | 11.3 | 11.3 | 23.6 | 23.6 |
| Case 3 | 69.6 | 10.5 | 10.5 | 24.3 | 24.3 |
| Case 4 | 69.6 | 11.5 | 11.0 | 24.0 | 23.1 |
| Case 5a | 69.6 | 10.5 | 10.5 | 24.3 | 24.3 |
| Case 5b | 69.6 | 12.0 | 12.0 | 22.8 | 22.8 |

Table G.1: The resulting calculated adjustments for the first mission mode testing

The corresponding mapped ballast adjustments, with the weights available, are represented in Table G.2. The first column represents how much weight will be added in total, while the other columns represents how much weight will be added to each point of adjustment.

| Cases | Total | Fore/Star | Fore/Port | Aft/Star | Aft/Port |
|---|---|---|---|---|---|
| Case 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 2 | 67.2 | 10.8 | 10.8 | 22.8 | 22.8 |
| Case 3 | 67.2 | 9.6 | 9.6 | 24.0 | 24.0 |
| Case 4 | 68.4 | 10.8 | 10.8 | 24.0 | 22.8 |
| Case 5a | 67.2 | 9.6 | 9.6 | 24.0 | 24.0 |
| Case 5b | 69.6 | 12.0 | 12.0 | 22.8 | 22.8 |

Table G.2: The resulting mapped adjustments for the first mission mode testing

## G.2 Test results for the pre mission mode

All the tests performed on the pre mission mode were done in accordance with the test routine presented in Section 6.3. The resulting mapped ballast adjustments, with the weights available, are presented in Table G.3. The table shows the amount of weight that should be added or removed relative to the ballast adjustment made in the first mission mode, where respectively 10.8 kg, 10.8 kg, 22.8 kg and 22.8 kg were added at the points of adjustment and the total became 1565.2 kg. The first column represents how much more weight should be added in total, while the other columns represent how much weight should be added to each point of adjustment.

| Cases | Total | Fore/Star | Fore/Port | Aft/Star | Aft/Port |
|---|---|---|---|---|---|
| Case 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 2a | 4.8 | 1.2 | 1.2 | 1.2 | 1.2 |
| Case 2b | -4.8 | -1.2 | -1.2 | -1.2 | -1.2 |
| Case 3 | 0.0 | 1.2 | 1.2 | -1.2 | -1.2 |
| Case 4 | 0.0 | 1.2 | -1.2 | 1.2 | -1.2 |
| Case 5 | 0.0 | -1.2 | 0.0 | 0.0 | 1.2 |
| Case 6a | 3.6 | 1.2 | 1.2 | 0.0 | 1.2 |
| Case 6b | -3.6 | 0.0 | -2.4 | 0.0 | -1.2 |
| Case 6c | 3.6 | 1.2 | 0.0 | 1.2 | 1.2 |
| Case 6d | -6.0 | -1.2 | 0.0 | -3.6 | -1.2 |

Table G.3: The resulting mapped ballast adjustments for the testing of the pre mission mode

The plots in Figure 7.6 show the ballast errors and the mapped ballast adjustment. The stars represent the ballast errors in each case, their positions' indicate the orientation errors, while their colors indicate the depth errors. A positive x-position indicates a negative pitch error and a positive y-position indicates a negative roll error. A black colored star indicates zero depth error, a purple star indicates a negative depth error, and a light blue star indicates a positive depth error. The dots represent the different adjustment points, their colors indicate the ballast adjustment made in the points. The dot in (1,1) is the fore/starboard point of adjustment, (1,-1) is the fore/port, (-1,1) is the aft/starboard and (-1,-1) is the aft/port. If the dot is green no weight has been added or removed, red indicates that weight has been added, while blue indicates that weight has been removed. The size of the ballast adjustments are not shown in the plots, only the signs and location of the ballast adjustments are indicated.