**NTNU – Trondheim**
Norwegian University of
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# Study of Critical Imaging Parameters and Variables for Environmental Monitoring Using an ROV with Experimental Results

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DEPARTMENT OF MARINE TECHNOLOGY

MASTER THESIS

# Study of Critical Imaging Parameters and Variables for Environmental Monitoring Using an ROV with Experimental Results

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# MASTER THESIS IN MARINE CYBERNETICS
# SPRING 2013
# FOR
## STUD. TECH. Paal Øvrebø Lohne

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### Work description

In order to fully develop an Integrated Environmental Monitoring System (IEM), there is a need to investigate the use of technology in underwater (UW) imaging. With the use of technology it is possible to capture and describe the important aspects of the status of an underwater environment. There exist different UW platforms and optical camera solutions that can be used together with a processing system to capture and analyze the data of the UW environment. This technology needs to be investigated in terms of technical and economic feasibilities as well as functional and operational requirements. The situation and need for the UW imaging system can vary, and therefore the investigation and test of the technology needs a well-planned implementation strategy. To further understand the potential as well as constraints that lie within UW imaging there is a need to run tests. This can be done by the use of a ROV, because it is easily deployable and can cover bigger areas, and therefore it can be used to support the right direction of the implementation strategy on an early stage. The goal in this master thesis is to develop, simulate and test a joystick control system for an ROV that results in valuable results that can be further analyzed for usability in underwater operations. And present an implementation strategy for the different UW platforms, based on the work done in the project thesis that was created during autumn 2012.

### Scope of work

- Review the project thesis from autumn 2012, implement feedback, and look into the suggestions for further work.
- Detail the different attributes for the underwater platforms.
- Investigate different joystick control methods for ROV Minerva to obtain good underwater images.
    - Further investigate the previous work done on joystick control.
    - Implement different manual, semi-automatic and automatic joystick control methods.
- Simulate the system for tuning of the control parameters
- Test the system through full scale experiments.
- Analyse the usability of joystick control based on the simulations and full scale experiments for ROV Minerva.
- Properly document the whole process.

The report shall be written in English and edited as a research report including literature survey, description of mathematical models, description of control algorithms, simulation results, model test results, discussion and a conclusion including a proposal for further work. Source code should be provided on a USB stick with code listing enclosed in appendix. It is supposed that Department of Marine Technology, NTNU, can use the results freely in its research work, unless otherwise agreed upon, by referring to the student's work. The thesis should be submitted in two copies within June 10th.

Advisers: Prof. Geir Johnsen and Dr. Martin Ludvigsen

Professor Asgeir J. Sørensen
Supervisor

# Abstract

In the oil and gas industry there is a high focus on integrating technology in the environmental monitoring happening before, during and after an offshore operation. In order to properly monitor the underwater environment, good images are needed. This can be achieved when proper equipment is used together with an underwater platform.

There is a need for a good strategy on how to do underwater imaging in different environments. The strategy is used by the personnel involved in the operation, and to ensure that the right equipment and platform is selected for the job. A strategy on underwater imaging is presented and can be applied to analyse environmental monitoring operations from a top-down approach. The lack of natural light in underwater operations and the effect this has on the visibility is also of great importance. This is presented and investigated through an imaging experiment.

Analyses of control methods have been conducted for ROV Minerva. This is a ROV that has been tested and developed through the AUR-Lab at the Department of Marine Technology at NTNU. In unknown areas and with poor visibility, it is important to maintain a good control of the ROV. The focus has been on how a joystick can be used with manual control and in a closed-loop control to make it easy for the pilot to navigate the vehicle. A joystick simulation system was developed for testing the joystick, and full scale experiments were conducted using ROV Minerva.

The tests show promising results for using a joystick in closed-loop control. The different methods can become an important tool when navigating mobile platforms during underwater operations in known and unknown areas. The conclusion cannot account for all situations, as it also highly depends on the experience of the pilot. Therefore the joystick control should be tailored for each operation.

# Sammendrag

I olje- og gassindustrien er det et høyt fokus på å integrere teknologi i overvåkingen av miljøet som skjer før, under og etter offshore operasjoner. Det er viktig med gode bilder for å overvåke miljøet korrekt og på en god måte. Dette kan oppnås ved at riktig utstyr blir brukt sammen med en teknologisk platform.

For å kunne utføre undervanns avbilding trengs en god implementasjonsstrategi. Strategien kan bli brukt av involvert personell, og for å sikre at riktig utstyr og platform er valgt for operasjonen. En strategi er presentert og kan brukes til å analysere miljøovervåkings-operasjoner fra et større perspektiv. Mangel på naturlig lys i undervanns-operasjoner og effekten av dette, er også av stor betydning. Dette er presentert og analysert gjennom et eksperiment utført på Trondheim Biologiske Stasjon.

Analyser av kontroll-metoder har blitt gjennomført for ROV Minerva. Dette er en ROV som er testet og utviklet gjennom AUR-Lab ved Institutt for Marin Teknikk ved NTNU. I ukjente områder og med dårlig sikt, er det viktig å kunne enkelt kontrollere ROVen som blir brukt. Fokuset i denne oppgaven har vært på hvordan en joystick kan brukes manuelt, og i et lukket kontroll-system for gjøre det enkelt for piloten navigere ROVen. Et joystick simulerings system ble utviklet for simulere interaksjonen mellom joystick og ROV, og fullskala eksprimenter ble utført ved bruk av ROV Minerva.

Testene viser lovende resultater for å bruke en joystick som referansegenerator i et lukket kontroll-system. De ulike kontroll-metodene kan bli et viktig verktøy i undervanns-operasjoner når det er et behov for å navigere mobile plattformer i kjente og ukjente områder. Det kan ikke konkluderes for alle situasjoner, fordi navigeringen av ROVen er også svært avhengig av hvor erfaren operatøren er. Joystick i lukket kontroll-system bør derfor skreddersys til hver enkelt operasjon.

# Preface

This thesis has been worked upon in the spring of 2013, based on a project thesis written in the autumn of 2012. This thesis is initiated through a project called MuDSCrIPE: Multi-Disciplinary Study of Critical Imaging Parameters and Variables for Environmental Monitoring. MuDSCrIPE is based on cooperation between the Department of Marine Technology and the Department of Biology. My supervisor has been Asgeir J. Sørensen and advisers Prof. Geir Johnsen and Dr. Martin Ludvigsen

The main goal of this thesis has been to investigate how an ROV can be used in underwater imaging. The focus was to look into underwater imaging from the strategic top-down view, the challenges assorted to the underwater environment, as well as through a concrete down-up view with the use of ROV Minerva.

The contribution from this thesis is highly dependent on the work done by previous students at the Institute of Marine Technology. The work done by Steffen Ø. Kørte during the spring of 2011 and Marianne Kirkeby in the autumn of 2010 has been very important for me to learn more about ROV Minerva. The work done by Espen M. Tolpinrud has been very useful to learn about the ROV Minerva control system. The cooperation with the Department of Biology also introduced new perspectives.

I would like to thank Prof. Geir Johnsen and master student Ingrid Kjerstad for introducing me to the Biological aspect of underwater imaging, and the interesting days at Trondheim Biological Station. Further I would like to thank Fredrik Dukan for always answering my questions, providing the help with a full scale test, and insight about the joystick control system. I would also like to thank my fellow students Raimon Andreas Olsen and Mika Sundland for the new perspectives and motivational support. At last I would like to thank my thesis supervisor Prof. Asgeir J. Sørensen for introducing me to this exciting field of environmental monitoring. He helped me define the direction of the thesis, and has always been available to provide much needed feedback and inspiration during a busy semester.

# Contents

# List of Figures

# Chapter 1

# Introduction

This thesis is a part of the project MuDSCrIPE: Multi-Disciplinary Study of Critical Imaging Parameters and Variables for Environmental Monitoring. This thesis aims to investigate challenges related to underwater (UW) imaging. MuDSCrIPE is based on cooperation between the Department of Biology and the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU).

This thesis is based on the work done in Strategy for Underwater Imaging - and Simulations for a ROV [Lohne, 2012]. Emphasis has been put on presenting a strategy needed for a good UW Imaging process, and investigating how this can be implemented on different platforms with the focus on joystick control for a Remotely Operated Vehicle (ROV) .

## 1.1 Background and Motivation

### 1.1.1 Integrated Environmental Monitoring

When offshore operations are being conducted the subsea environment is exposed to equipment and people. In order to analyse the impact the operations have on the environment, independent 3rd party organizations are out in the field collecting samples as well as visual surveys. The current practice of manual monitoring of the environment is slow as well as time consuming.

Other challenges are [Statoil, 2012]:

- Flexibility
    - Monitoring must be suited to the actual habitat

    - Physical sampling may harm sensitive habitats

- Response time of point sampling
    - Significant time lag between impact occurrence and detection
- Cost-effectiveness
    - Can be improved through interaction in design and operations

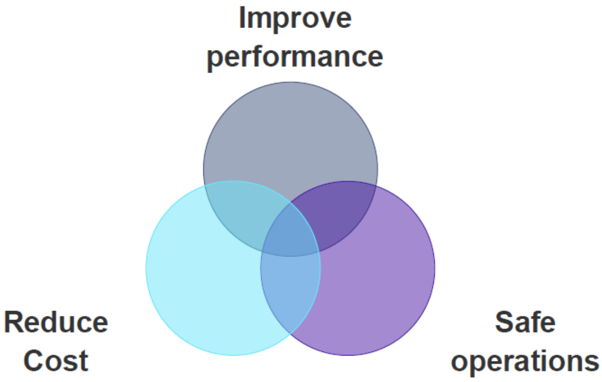


Figure 1.1: The purpose of Integrated Environmental Monitoring. Courtesy: Statoil AS.

By introducing a continuous environmental monitoring these challenges can be solved. As seen in Figure 1.1 the goal of Integrated Environmental Monitoring (IEM) is to reduce the cost, improve the performance and ensure safe monitoring operations. In IEM available technology is combined with human interaction to provide a continuous monitoring of the environment. This proves a unique opportunity to monitor data and send the needed information to the right place at the right time.

In order to fully develop an IEM system, there is a need to investigate the use of technology in UW imaging. Because the right use of technology makes it possible to capture and describe many important aspects of the UW environment. The quality of the data is important, and the wrong choice of platform might not provide the needed results.

### 1.1.2 Underwater Imaging

There are different UW platforms and optical camera solutions that can be used together with a processing system to capture and analyse the data of the environment.

To ensure good images there is a need to investigate the effects of technical and environmental factors affecting the image quality. The camera solution is dependent on:

1. Monitoring distance (d) to objects of interest (OOI)
2. Monitoring angle ($\varphi$)
3. Light source (L)
4. Position accuracy

The environment where the pictures are taken has certain Inherent Optical Properties (IOP) that affects the quality of the images. The optical properties of the water change with the season, and this needs to be taken into account and analysed as well.

The monitoring distance, the IOP of water and light source will be further discussed. The focus will be on looking into how an ROV can achieve a good position accuracy, and move with small velocity variations to acquire good images.

### 1.1.3 Important Terms used in Underwater Imaging

As UW imaging requires collaboration between several academic areas, it is important to have a common understanding of the most important academic terms used in the work. To ensure consistency in the academic terms, the following list has been developed in cooperation between the Department of Biology and the Department of Marine Technology:

#### General terms

- Objects Of Interest (OOI)
    - Bio-geo-chemical-manmade objects of interest (habitats, minerals, bottom types, life forms or hardware which is interesting to investigate and further analyze). Main target of interest.

- Spatial coverage
  - Spatial coverage specifies the geographic, horizontal and vertical (altitude, depth) coverage of the data.
- Spatial resolution
  - Image pixel resolution (units: mm, m or km)
- Temporal resolution
  - Cover one specific spot/or area during a time-series.
- Spectral resolution
  - Wavelength resolution (pr nm or wavebands (eg. 5 nm bandwidth).
- Inherent Optical Properties (IOP)
  - The optical properties of water; which is a function of the optical properties (light absorption and scattering) of the water itself, coloured dissolved organic matter (cDOM), total suspended matter (TSM) and phytoplankton (chl a).

**Camera Related terms**

- Aperture
  - This is the opening on the camera that determines the cone angle of a bundle of rays that come to a focus in the image plane. It determines how collimated (=parallel) the admitted rays are. Related to depth-of-field in an optical image.
- Shutter Speed
  - Determines the effective length of time that the shutter (device that allows light to pass for a determined period of time) will stay open when taking a picture.
- ISO
  - Determines how sensitive the image chip (CCD or CMOS) is to light.
- Illumination even-ness (avoid over/under exposure)
  - Most images do not have an even illuminated surface crucial for numerical image processing (eg. photo-mosaics).

  - Overexposure(=blooming)
    - Appears white by eye with no signature (loss of data).
  - Underexposure
    - Appears black by eye with no signature (loss of data).

**Platforms (Instrument Carriers)**

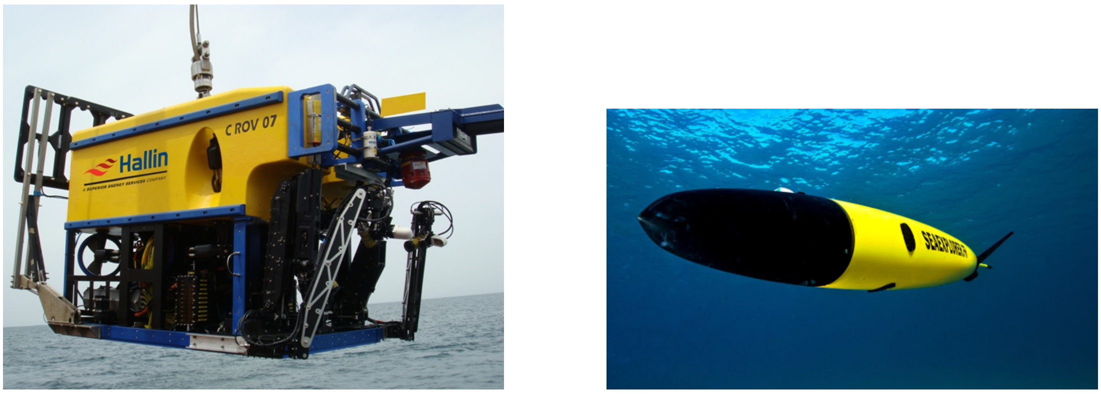
- Tripod (lander)
  - Situated on a permanent location. Custom made underwater tripod for scanning of the sea-floor. A variety of cameras and sensors can be attached.
- Autonomous Underwater Vehicle (AUV)
  - An unmanned vehicle that travels underwater without the need of operator input during operations. This means that it is moving freely without any cables or restrained connections to other vehicles.
- Remotely Operated Vehicle (ROV)
  - An unmanned vehicle that travels underwater and is controlled and powered from the surface by an operator/pilot via an umbilical cable.
- SCUBA Diver
  - A person operating underwater using a self-contained underwater breathing apparatus.

These terms are based on experience and data found in [Mobley, 1994], [Sakshaug et al., 2009], [Johnsen et al., 2009], [Johnsen et al., 2012], [Bricaud et al., 1981], [Kirk, 1994] and [Jerlov, 1968].

### 1.1.4 Unmanned Underwater Vehicles

The starting history of Unmanned Underwater Vehicles (UUVs) may be tracked back to the self-propelled torpedo which was perfected in 1868 by Whitehead [Roberts and Sutton, 2006]. The US Navy contributed further through developing the design and construction of cable controlled underwater recovery vehicles. The commercial breakthrough for the use of UUVs came when oil was discovered in the North Sea. In these operations ROVs began and continued to be used extensively. As the offshore industry continued to develop, the interest and range of usage increased more and more with the continuously growing need from the oil sector. In the beginning most of the development was for the ROV, but as control systems got more intelligent the potential use of Autonomous Underwater Vehicles (AUVs) also improved.

The name UUV is used as a common term for both ROV and AUV. An AUV is a marine craft which operates independently and fulfils a mission without being constantly monitored and controlled. It has its own power supply, is built for higher speed and is typically under-actuated. Typical tasks for an AUV can be monitoring of cables and seabed surveys. Figure 1.2b shows the ACSA SeaExplorer AUV, and the torpedo like design which is typical for AUVs.



(a) The C-ROV manufactured by Hallin Marine.

(b) The AUV SeaExplorer (ACSA) about to surface.

Figure 1.2: Two different typical UUVs.

A ROV on the other hand is a marine vehicle that can receive instructions from an operator through an umbilical cable connecting the ROV with a ship on the surface. The ROV is not built with considerations for hydrodynamic performance and is often box shaped. They are fully actuated and can be installed with different sensors and equipment depending on the task they have to perform. Figure 1.2a shows the C-ROV (manufactured by Hallin Marine), and the typical box shape design which is a clear distinction from the AUV.

### 1.1.5 The ROV Minerva

Minerva is a SUB-fighter 7500 ROV made by Sperre AS in 2003 for NTNU. Figure 1.3 show ROV Minerva with the basic equipment. Minerva has been used in biological research and sampling, testing of equipment and development of new research technology, archaeological surveys, supplying ground truth in geological investigations and much else [Marine, 2012].

Minerva communicates with the surface vessel through a 600 $m$ umbilical cable, and it is usually deployed from the NTNU research vessel (RV) Gunnerus. The ROV can be equipped with additional lights, an extra manipulator arm and other special purpose tools depending on the operations. All the systems needed to operate the ROV are fitted inside a 15 feet container. The detailed specifications for ROV Minerva is given in Table 1.1.

Figure 1.3: The ROV Minerva. Photo:Johanna Jarnegren

### 1.1.6 Marine Control Structure

Figure 1.4 shows the overview of marine control structure. The top level is where the operational strategy is decided, as well as the mission planning. This is usually aspects of the operation that is very time consuming, and should be done off-line in advance.

The local optimization has a higher response time and is the highest level of real-time control. This is where the guidance system is performed.

High-level control consists of the controller, observer and further thrust allocation to the different thrusters.

The low-level control is the local control happening at the thrusters. This can include anti-spin in extreme weather conditions, and this form of control is very fast.

The work in this thesis will be a combination of the top level operational strategy, high-level control structure, and guidance through the use of joystick methods.

| | |
|---|---|
| Dimensions | LWH 144x82x81 cm |
| Weight (air) | 485 kg |
| Payload | 20 kg approx. |
| Max depth | 700 m |
| Power input | 230 VAC, single phase 10 kW |
| Thrusters | Horizontal: 2 x 2000 W<br>Vertical: 2 x 2000 W<br>Lateral: 1 x 2000 W |
| Speed | Horizontal: 2.0 knot<br>Vertical: 1.2 knot<br>Lateral: 1.3 knot<br>Turn rate: 60°/$s$ |
| Camera 1 & 2 | PAL colour CCD<br>460 TV lines, 0.1 lux |
| Camera 3 | PAL colour Zoom<br>460 TV lines, 0.1 lux |
| Camera 4 | 3CCD Zoom High resolution<br>PAL 530 TV lines, 15 lux |
| Sonar | Kongsberg Simrad MS 1000 (675 kHz)<br>Beam width: 1.4° x 22° Fan (nominal)<br>Range: 0.5-100 m (typical)<br>Scan angle: 360° continous [Sonar-MS1000, 2012] |
| Manipulators | One 5-function hydraulic arm (HLK-HD5)<br>One 1-function electric |
| Light | 4 x 250 W halogen lights (4 channel light dimmer) |
| Sensors | 100 bar pressure gauge<br>Fluxgate compass<br>CRS03 silicon rate sensor [Systems, 2012]<br>Teledyne RDI Workhouse Doppler velocity log (DVL) [Instruments, 2012]<br>MRU6 from Kongsberg seatex [Maritime, 2012]<br>leakage detector |

Table 1.1: ROV Minerva Specifications [Dukan et al., 2011]

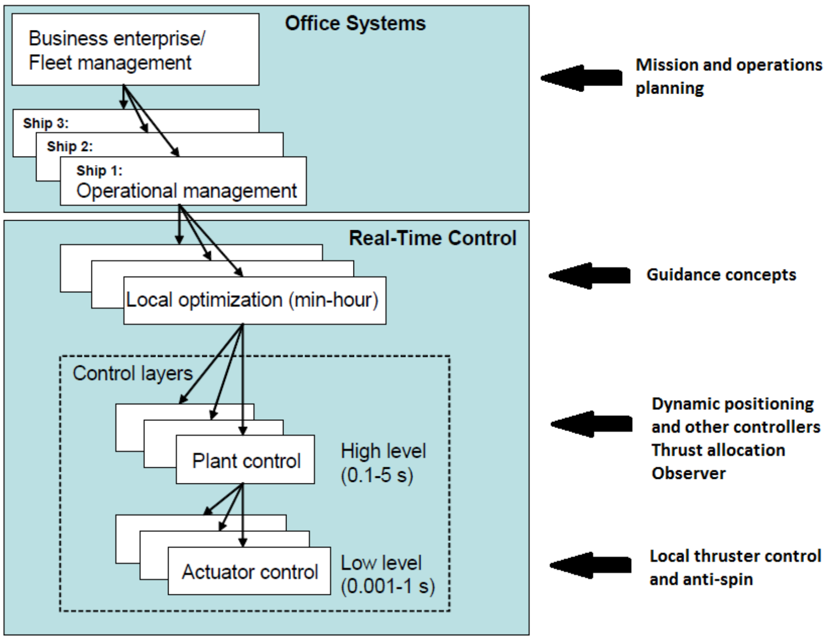


Figure 1.4: Overview of the marine control structure [Sørensen, 2012].

# 1.2 Previous Work

## 1.2.1 Control Systems for ROV Minerva

There was an attempt in Svendby [2007] to design a robust adaptive controller for ROV Minerva. The controller performed well in simulations, but the performance during live tests was not good enough due to lack of measurements and sensor noise.

Previous work at the Applied Underwater and Robotics Laboratory (AUR-lab) has provided further advancement of ROV control. The work done on a Dynamic Positioning (DP) system for ROV Minerva can be further read about in Dukan et al. [2011] where good results were achieved for the observer and control system. This is based on some of the notable work done by Kirkeby [2010] and Candeloro [2011]. The work done by Kørte [2011] focused on different guidance principles and guidance strategies. A more practical approach to manual joystick control is suggested in Dukan and Sørensen [2012], where the focus was on a joystick with closed-loop control functions. A restructuring of the Minerva control system can be found in Tolpinrud [2012], and made the system more user-friendly.

### 1.2.2 Images and Light in the Underwater Environment

The role of light and identifying factors that are influencing the conditions in the sea have been thoroughly documented in [Sakshaug et al., 2009]. Taking images to be used in underwater photo mosaic for archaeological purposes are detailed in Ballard et al. [2000] and Singh et al. [2004]. Expeditions using ROV Minerva for photo mosaic on a marine biological site was conducted by Ludvigsen et al. [2007].

This work done in the different fields, create a solid basis that can be further utilised and implemented in different operations.

## 1.3 Contributions

The contribution of this thesis is:

- Strategic planning for UW imaging and platform attributes.
    - A strategy that can be used as a tool when planning and executing UW imaging operations. The proposed strategy is presented in Section 2.1. Together with the strategy, an overview of the platforms and their attributes was developed. The attributes for the different platforms is outlined in Section 2.2.
- Underwater experiments on light conditions.
    - A first step to analyse the underwater conditions when gathering data without natural light is presented in Section 2.3 and Section 2.4. These sections were conducted and written together with Ingrid Kjerstad from the Department of Biology.
- Stand-alone simulation system for joystick control.
    - A system to simulate the joystick-ROV interactions without the need of the full control system for ROV Minerva was developed and is presented in Section 4.5.

## 1.4 Outline of Thesis

**Chapter 2** contains the overall analysis of UW imaging. This focuses on an overall strategy, the different platform attributes, and how the light in the UW environment is a challenge for the visual feedback.

**Chapter 3** introduces the purpose of monitoring an OOI exemplified through different control strategies, with the focus on joystick control. The different joystick control methods are presented as well as the overview of the control structure for ROV Minerva.

**Chapter 4** introduces the 6 DOF process plant model for ROV Minerva, and the simplified 4 DOF control plant model. Further it looks into the joystick configuration, and how it can be related to the ROV. Different relations trough thrust and velocity is presented together with the original and modified velocity reference model. A description of a stand-alone simulation system for a joystick in a closed-loop control is also presented.

**Chapter 5** contains the simulation and discussions of the results from the joystick control system. Joystick control methods are evaluated, and there is a discussion based on the results from the simulations of the different scenarios.

**Chapter 6** presents the full scale tests that were conducted outside of the Trondheim Biological Station this may. The full scale tests focused on joystick in a closed-loop position control compared to joystick with manual control.

# Chapter 2

# Underwater Imaging

This chapter presents a suggested strategy to use when planning an underwater imaging operation. To complement the strategy, there is an overview of the different platforms and their attributes. As the visibility is a key factor in underwater operations, the behaviour of light is presented with experimental results.

## 2.1 Strategy for Underwater Imaging

In order to decide which platforms to use for different operations, there is a need to define what we want to achieve with UW imaging. In this thesis a strategy for UW Imaging is presented. This is meant as a tool to make the decision processes easier when planning an UW operation. The strategic plan is based on a long-term vision, and from the vision different objectives are developed.

It is possible to divide the objectives into goals to make the planning easier. The goals will not be focused on in this thesis, as they require more input from everyone involved in the operation. The objectives will have different functional requirements as seen in Figure 2.1. These requirements can be further matched with the different technological platforms.

### 2.1.1 Vision

Use technology to efficiently produce a full overview of the underwater environment before, during and after an operation to ensure that the activities did not negatively influence the natural environment in the area of the operation.

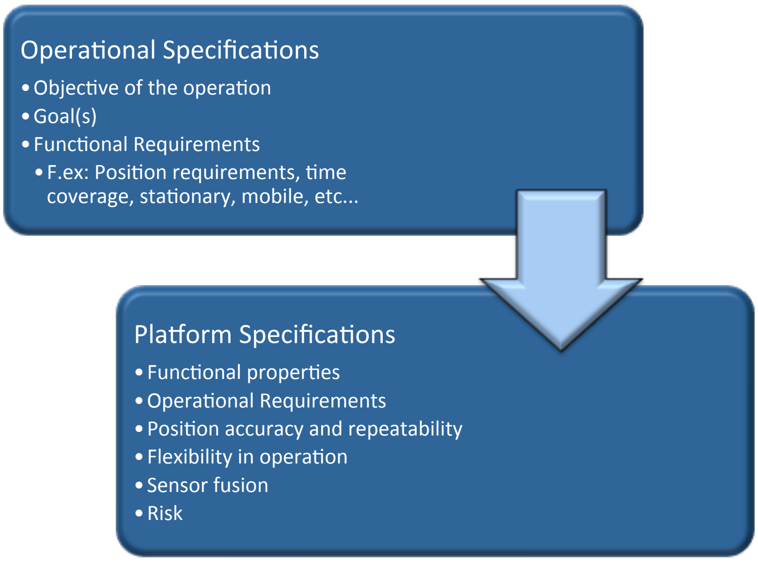


Figure 2.1: The elements to be considered when deciding operational specifications and platform specifications, and the decision flow.

### 2.1.2 Objectives

The objectives for UW Imaging can be divided according to:

- Long term

  Long term objectives have a timespan of days or even years. During the operation data is recorded constantly or with regular intervals depending on the need.

  Long term objectives can be divided into:

  - Monitor a specific area
    - This objective consists of having a temporal resolution of an area of interest. The changes in the area can be investigated and analysed. One way to achieve this objective can f.ex be to move over an area every hour and generate images that are to be analysed. The same procedure takes place over several weeks/months/years.
  - Monitor the development of an OOI
    - Instead of covering an area, this objective focuses on one OOI, or a certain specific location that is then monitored with a regular interval.

- Short term

  Short term objectives have a timespan of a day or a week. In the short term objectives all the data is collected within a short period of time, and is post-processed for detailed analysis.

  Short term objectives can be divided into:

  - Map an area for further analysis
    - This objective consists of doing UW imaging to cover an area once. Afterwards the gathered data can be post-processed to find OOIs that can be further investigated through a long term objective.
  - Check the current status of an OOI
    - In this objective the location of an OOI is already known. The operation consists of investigating the current status of the OOI without a direct follow-up.

The different objectives will have different functional requirements. Typical for the long term objectives, the temporal resolution is important, while this is less significant for the short term objectives. Spatial coverage is present in both cases as long as there is an area that is to be investigated.

The different objectives and their functional requirements are summarised in Table 2.1. By using this table it is possible to get an overview of the functional requirements that the platforms need to meet in order to be suited for the operation.

| **Time-frame** | **Objective** | **Functional Requirements** |
|---|---|---|
| Long Term (Months - Years) | Monitor a specific area | Mobile, spatial coverage, can be stationary |
| | Monitor the development of an OOI | Stationary, temporal resolution, automatic generate data |
| Short Term (hours - days) | Map an area for further analysis | Mobile, spatial coverage, automated control |
| | Check current status of an OOI | Mobile, manual control (can be combined with automated control) |

Table 2.1: Overview of the objectives and their functional requirements

## 2.2 Platform Attributes

When the objectives are decided, the functional requirements can be matched with the functional properties of the platforms. It is therefore important to have a good overview of the platform attributes in order to compare which platform is most suited for the operation.

The four relevant platforms are ROV, AUV, lander and diver. Based on experimental data, previous experience and empirical observations it is possible to say something about the strengths and shortcomings for each platform. Each platform is presented with the data based on experience. In the end there is a table summarizing the most important aspects for each platform. For each platform the following parameters will be further detailed:

- Functional properties for the platform
    - Each platform have their own functional properties. Some platforms are mobile, while others are stationary. The platforms have different properties depending on how they are formed and therefore they satisfy the functional requirements differently.

- Operational requirements
  - Operational requirements covers the weather window the platforms can operate in. This involves visibility, wave, wind and currents and the sensitivity each platform has for these factors. Operational requirements also cover the availability and how easy it is to get into operational modus.
- Position accuracy and repeatability
  - For some operational objectives there is a high need of precision as well as the chance to return to the same location more than once.
- Flexibility in operation
  - The platforms need to be considered on how they can adapt to big changes in the operational conditions.
- Sensor fusion
  - During the operation it might be beneficial to use many different types of sensors. Therefore we have to analyse if the platforms can support more sensors during an operation.
- Risk
  - The risks are the potential challenges and problems that can occur for each platform. This is where questions are raised that needs to be investigated and solved to ensure a successful operation.
- Not included due to lack of data
  - Capex - defined as money used by the owners of the UW platform to increase its value.
  - Opex - refers to expenses used for ordinary use such as operational costs, general and administrative expenses.

### 2.2.1 ROV

A ROV is remotely controlled by an operator, and the vehicle is communicating with the surface through an umbilical cable. This cable also provides power to the ROV, and live data can be sent through this cable to the operator during an operation.

- Functional properties
  - Mobile. The ROV is able to move freely underwater and the depth depends on the available length of the umbilical cable.
  - Partly Stationary. The ROV can use its thrusters to stay stationary during operation. As this is thruster based, it cannot achieve a perfect precision.
  - Manual control and automated control. It is possible to control the ROV directly through a joystick or implement a control system that takes care of steering the ROV.
- Operational requirements
  - Most weather conditions. It is possible to use the ROV in most weather conditions, and the vehicle is not strongly affected by wind and waves. This is most critical in the deployment phase of the operation.
  - Available at most times. To use a ROV it is needed to have an operator and a ship available. There is not a need for special technicians as long as the group performing the operation knows the vehicle.
- Position accuracy and repeatability
  - Limited position accuracy. As the ROV is kept stable by its own thrusters, the accuracy delivered depends on the control system that is implemented. Previous tests have shown an error of 0.2-0.3 meters in surge and sway during station-keeping.
  - Limited repeatability. To navigate a ROV perfectly back to the same location is not possible. Therefore a perfect repeatability cannot be achieved.
- Flexibility in operation
  - Limited flexibility. Using a ROV in an operation should be well scheduled and planned in advance. The ROV is highly technical, and problems can appear if sudden changes occur or new operational demands are introduced.

- Sensor fusion
  - Good sensor fusion. The ROV can carry several sensors. The limitation of equipment is based on the size of the ROV and the available thrust capacity. Considerations should be taken related to symmetry in order to not make the ROV unstable. A more detailed study of this will be presented in Part II.
- Risk
  - Software and Hardware errors. When executing an operation with a ROV, there is often a control system involved. The software and hardware components have to work as planned, and the communication with the ROV needs to run smooth. There are many components here that can fail.
  - Configuration time. If not everything is tested in advance, or there are unforeseen parameters in the environment, there might be extra configuration time needed during the operation.

### 2.2.2 AUV

An AUV is pre-configured and runs independently until the mission objective is completed, and it returns to the main ship.

- Functional properties
  - Mobile. The AUV is torpedo shaped and the typical use is to have the AUV follow a path using its thrusters for moving.
  - Passively stationary. The AUV can be programmed to stop the thrusters and float passively at a specific depth, and in this way stay stationary at one location.
  - Automated control. The AUV is implemented with a control system, and there are only limited control changes that can be communicated during an operation.
- Operational requirements
  - Most weather conditions. It is possible to use the AUV in most weather conditions, and the vehicle is not strongly affected by wind and waves. This is most critical in the deployment phase of the operation. The biggest limitation is the underwater current. If the current is too strong it can be a challenge for the AUV to navigate.

  - Available at most times. The AUV is available as long as there is a ship available, and the team that uses the AUV for the operation.

- Position accuracy and repeatability
  - Path and tracking accuracy. As the AUV is highly mobile it can only follow a path accurately, and it cannot stay in one position for a longer time.
  - Limited repeatability. As the AUV operates independently underwater, it is hard to navigate the exact same path twice. It can however move over an area several times with a small offset.

- Flexibility in operation
  - Limited flexibility. An AUV operation should be scheduled and planned well in advance. Once the AUV is released from the ship, it will move independently, and the control system and setup on the AUV should by that time already be well defined. It is therefore limited how big changes can happen once the operation has started.

- Sensor fusion
  - Limited sensor fusion. The AUV has limited space in the hull for sensors and equipment, it is therefore limited how many sensors can be equipped per operation.

- Risk
  - Software and Hardware errors. When executing an operation with an AUV, there is usually a control system that is dependent on the model of the AUV. During the operation there is a wireless communication with the surface, but no direct contact. If something happens during the operation, the AUV needs to have an emergency system that ensures that the ship on the surface can locate the AUV. This means that if something happens during an operation the ship needs to locate the AUV and recover it to the ship, resulting in a full stop of the operation.
  - Configuration time. If everything is not properly tested in advance, or there are unforeseen parameters in the environment, there might be extra configuration time needed during the operation instead of accomplishing the desired mission objective.

### 2.2.3 Lander

A lander is typically a tripod that is lowered from a ship and mounted on the seabed.

- Functional properties
  - Stationary. The lander is lowered to one specific location, and do not have any form of thrusters or wheels to move around. The lander can then be stationary on one location for some weeks and up to several years depending on the operation objective.
- Operational requirements
  - All weather conditions. The only time the lander is dependent on the weather is when it is installed on the seabed.
- Position accuracy and repeatability
  - Very good position accuracy. The lander will provide good position accuracy because it is installed stationary on the seabed.
  - Good repeatability. When monitoring the development of an OOI, the lander has a very good temporal resolution. The repeatability is high for the whole deployment period.
- Flexibility in operation
  - Limited flexibility. There can be changes in the operational objectives until the lander is deployed.
- Sensor fusion
  - High sensor fusion. The lander can support several sensors.
- Risk
  - Plankton growth. As the lander might be deployed for several years there can be a high development of plankton growth on the installed sensors and equipment.

### 2.2.4 Diver

A diver can be one person or a team of people going underwater to perform a task or operation.

- Functional properties
  - Mobile. The divers are free to move in the sea as they desire and as the operation objective requires.
  - Partly stationary. Divers can also stop on one location to perform a task, but they can only be stationary for a certain time interval, depending on available resources.
  - Depth dependent. There is a limitation to how deep a diver can go, and this makes a diver unsuitable for operation objectives that require deep waters.
- Operational requirements
  - Limited weather conditions. A diving operation can only be performed when the environmental forces are not a threat to the safety of the divers.
- Position accuracy and repeatability
  - Limited position accuracy.
    - When the divers use equipment underwater, they cannot achieve perfect positioning as they are mobile and moving around.
  - Limited repeatability.
    - The divers can come back to an area to perform the same task, but unless there is something mounted on the seabed they will not have a good enough reference to repeat the operation with precise accuracy.
- Flexibility in operation
  - Highly flexible. The divers are flexible as they can easily adapt to new mission objectives during an operation.
- Sensor fusion
  - Limited sensor fusion. When doing an operation with divers they can only bring the equipment they can carry. They typically don't have different sensors as part of the equipment.

- Risk
    -

### 2.2.5 Summary of the Attributes

Table 2.2 gives a good overview of the different platforms and the main attributes to be considered when there is a need for a platform in an operation. This can be used as an overview without all the details and just the key information.

| Platform | Functional Properties | Operational Requirements | Position Accuracy and Repeatability | Flexibility In Operation | Sensor Fusion | Risk |
|---|---|---|---|---|---|---|
| ROV | Mobile<br>Partly stationary<br>Manual control and automated control | Most weather conditions<br>Available at most times | Limited position accuracy<br>Limited repeatability | Limited flexibility | Good sensor fusion | Software and hardware errors<br>Extended configuration time |
| AUV | Mobile<br>Passively stationary<br>Automated control | Most weather conditions<br>Available at most times | Path and tracking accuracy<br>Limited repeatability | Limited flexibility | Limited sensor fusion | Software and hardware errors<br>Extended configuration time |
| Lander | Stationary | All weather conditions | Very good position accuracy<br>Good repeatability | Limited flexibility | High sensor fusion | Plankton growth |
| Diver | Mobile<br>Partly stationary<br>Depth dependent | Limited weather conditions | Limited position accuracy<br>Limited repeatability | Highly flexible | Limited sensor fusion | - |

Table 2.2: Overview of the different platforms and their Attributes

## 2.3 Light and Inherent Optical Properties

An important aspect of working in the depths is the lack of natural light. The water has other properties then air, and therefore these needs to be studied as well. It does not help with a suitable platform if the platform equipment does not fulfil the task of the environment it will operate in.

There are severe limitations of optical imaging in the underwater environment. There is a rapid attenuation of the electromagnetic radiation, and ambient lighting is practically non-existent after the first few tens of meters of depth [Pizarro and Singh, 2003]. This makes it extra challenging to take good images, and usually means that there is a need for an extra light source.

Visible light form a narrow band of electromagnetic radiation. The wave mode of light is described by frequencies and wavelengths. A typical human eye will respond to light in the wavelengths from 400 $nm$ to 700 $nm$. Each wavelength is assorted with a colour. Particles, and especially phytoplankton absorbs light, but is mostly focused on some wavelengths related to blue light. The water itself absorbs the wavelengths related to red light [Sakshaug et al., 2009].

In Figure 2.2 we can see how the different wavelengths of light is absorbed as it gets deeper. When sunlight enters, the dotted lines show how the red and green light is absorbed, and only the blue light is reflected. In the sea, and especially in the fjords, there are a high number of particles that absorbs the blue light, and the red is absorbed by the water itself. This makes the fjords look greener and this is reflected on the images taken. In more open areas like the Atlantic, there is a less concentration of particles, and thus the water stays blue.

Further in the depth more light is absorbed, as well as from different matter and organisms in the water. This is given by the Inherent Optical Properties (IOPs) of sea water, which is a function of the optical properties (light absorption and scattering) of the water itself, coloured Dissolved Organic Matter (cDOM), Total Suspended Matter (TSM) and Chlorophyll a (Chla) [Johnsen et al., 2009]. This depends on the season, and also the type of activity. This can be critical when investigating OOIs close to the seabed, as high activity can stir up unwanted matter and further disable the light source.

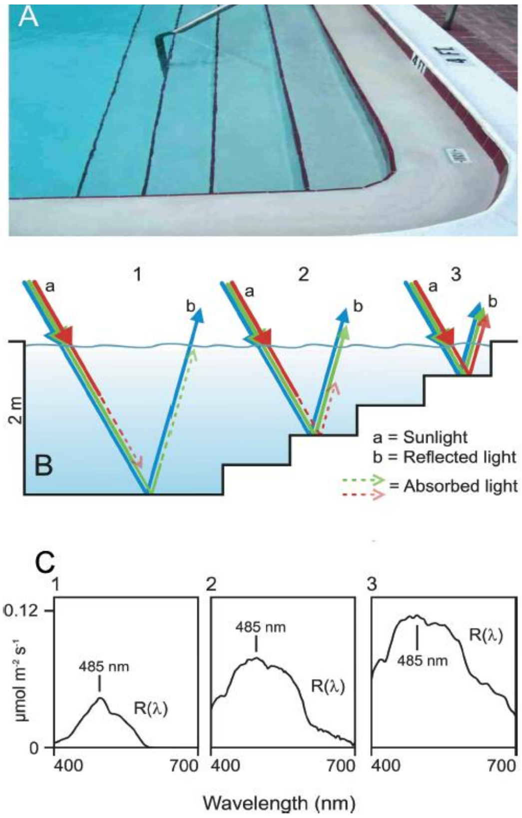


Figure 2.2: Absorption of the reflected sunlight in different water depths. Photo:Vibeke Sakshaug, Illustrations: Zsolt Volent (B,C), courtesy: [Sakshaug et al., 2009].

To measure available light it is possible to look at the Photosynthetically Available Radiation (PAR), which is the total radiation from 400 $nm$ to 700 $nm$. PAR is also defined as the level of available light that the human eye can register, and therefore it can be used to measure the amount of light available when taking an image. The level of absorbed light is found by multiplying a narrow wavelength interval of the absorption spectrum with the irradiance in the same wavelength interval [Sakshaug et al., 2009]. The sum over all the wavelengths then give the complete overview of the absorbed light, given in equation (2.1).

$$\text{Absorbed light (PAR)} = \sum_{400}^{700} E_0(\lambda) a_\phi^*(\lambda) \tag{2.1}$$

where $E_0$ is the irradiance at wavelength $\lambda$ and $a_\phi^*(\lambda)$ is the absorption coefficient at the same wavelength.

Using these measurements it is possible to say something about the light needed, and the challenges of visibility in the underwater environment.

## 2.4 Taking Underwater Images with Experimental Results

To further investigate the influence of the IOPs of water, there were some experiments conducted at Trondheim Biological Station (TBS) during April 2013. The focus was to simulate a situation in the deep sea, and was therefore conducted at night.

This experiment was done with two scuba divers, in a 5m deep test-pool using a platform consisting of two halogen lights and a Canon EOS 5D Mark II camera in a underwater house. The test-pool imported seawater from 120m depth in the Trondheimsfjord. The goal was to take a picture of a white reference plate every meter, starting from 5m away, up to 1m close to the plate.

### 2.4.1 Sensors

Two different types of sensors were used during the testing.

- ECO-PAR
    - Provides highly accurate measurements of PAR (400 $nm$ to 700 $nm$) in all aquatic environments. Specifications are listed in Table 2.3.
- ECO Triplet-wB
    - This sensor is configured for biogeochemical measurements, such as chlorophyll a, cDOM, fluorescence and red backscattering. It provides multiple measurements in a compact design. Specifications are listed in Table 2.4.

The ECO-PAR sensor was used to measure light during the whole process, and for each of the images taken. The ECO Triplet-wB was inserted in the water before the testing started and in the end after everyone had left the test-pool. This was done in order to check if the activity when taking the images had changed the properties of the water.

| **Mechanical** | |
|---|---|
| **Diameter** | 6,3 cm |
| **Length** | 12,7 cm |
| **Weight in air** | 0,4 kg |
| **Weight in water** | 0,02kg |
| **Pressure housing** | Acetal co-polymer |
| **Temperature range** | 0-30 deg C |
| **Depth rating** | 200 m |
| **Optical** | |
| **Collector area** | 86 $mm^2$ |
| **Detectors** | 17 $mm^2$ silicon photodiode |
| **Field of view** | Cosine response (within 3% @ 0-60 deg C) |

Table 2.3: Specifications for ECO-PAR.

| **Mechanical** | |
|---|---|
| **Diameter** | 8,08 cm |
| **Length** | 33,34 cm |
| **Weight in air** | 2,1 kg |
| **Weight in water** | 0,43 kg |
| **Material** | Acetal co-polymer |
| **Environmental** | |
| **Temperature** | 0-30 deg C |
| **Depth rating** | 600m |

Table 2.4: Specifications for ECO Triplet-wB.

### 2.4.2 Results

When first analysing the results from the sensors after the experiment it turns out that the light measurements are not coherent. Therefore the full results of the experiment are not taken into account. We will investigate one image 4m away from the reference plate as seen in Figure 2.3, and 2m away as seen in Figure 2.4. The results are still enough to demonstrate the lack of visibility that occurs in deep water with no natural light available.

| **Distance** | **ECO-PAR** | **Time instance** | **cDOM** |
|---|---|---|---|
| 4m | 0,0711 $[\frac{\mu mol}{m^2/s}]$ | Before experiment | 1,6442 $[ppb]$ |
| 2m | 0,1555 $[\frac{\mu mol}{m^2/s}]$ | After experiment | 2,0210 $[ppb]$ |

Table 2.5: Light available at 4m and 2m away from the reference plate, and cDOM levels before and after the experiment was conducted.

From Figure 2.3 and 2.4 we see that the visibility of the reference plate is clearly improved when moving closer. This can also be verified from the measurements of available light. As seen in Table 2.5 the available light at the target is approximately doubled when moving from 4m to 2m.

Another important source that absorbs light is the matter dissolved in the water. The cDOM was measured for 5min before the experiment and 5min after the experiment. Table 2.5 show the average for these two time instances. As expected the amount of cDOM also increased during the experiment due to the movement of the scuba divers. The same situation can easily occur with a ROV moving close to the seabed with a high thruster use.

The lack of visibility is of relevance when using platforms such as an ROV. The results clearly demonstrate the lack of visibility the ROV pilot will have when entering new and unknown areas. In these situations the OOIs might not be visible until the platform is very close. Therefore it is important that the mobile platforms can be navigated with a stable and accurate control system. It is important that the pilot can adapt to sudden changes as well as keeping the movements close to the seabed smooth, such that sudden changes in direction does not create more sediments that lower the visibility.

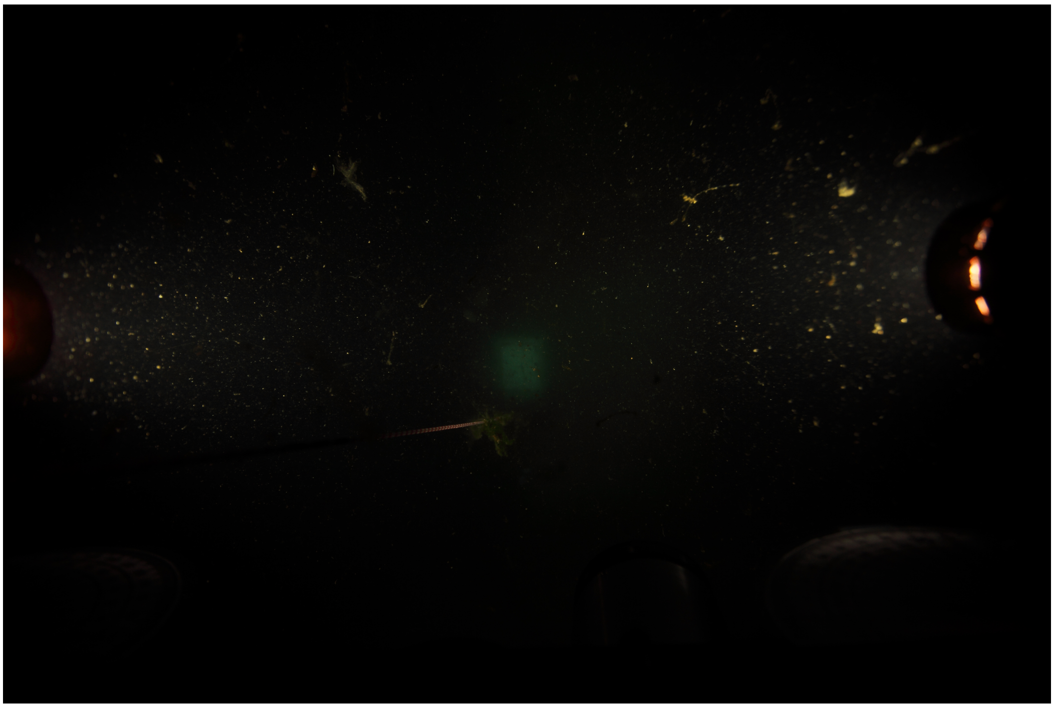


Figure 2.3: Image taken 4m away from the reference plate with artificial light.

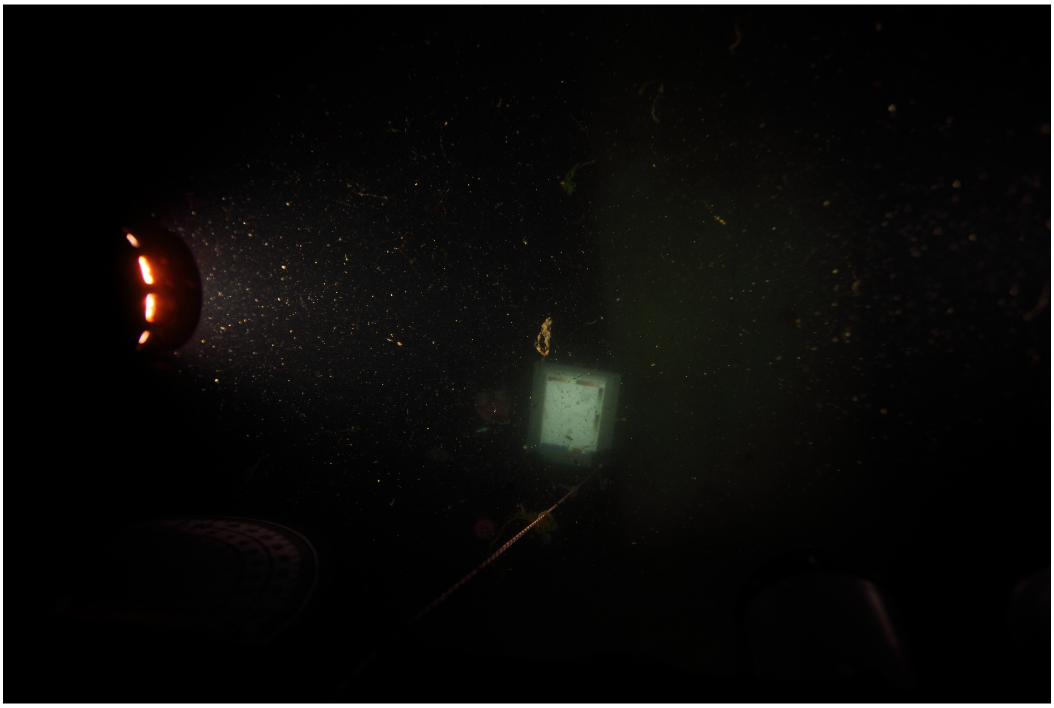


Figure 2.4: Image taken 2m away from the reference plate with artificial light.

# Chapter 3

# Methods to Investigate an Object of Interest

There are different methods that can be used to investigate an OOI with an ROV. To accomplish the operational objectives, some methods will be suggested where the focus is on the control of the ROV with a joystick. This chapter also presents an overview of the control structure in order to provide the full picture.

## 3.1 Purpose of Monitoring an OOI

There are many different OOIs that can be of interest to study or investigate. The OOIs can either be stationary or moving because of currents or other environmental disturbances.

The reason for taking images of an OOI can vary depending on the institution that is interested. Within the field of biology it is typically interesting to study the development of biological objects and how they change due to human interaction. For offshore companies on the other hand there might be an interest to study pipelines and other subsea installations in order to ensure that everything is working properly, as well to document that the environment is not disturbed by the operations.

The different OOIs vary in size, location and need for short term or long term study. Therefore the requirements for repeatability and accuracy vary for each OOI. To ensure good usable images it is therefore important to run simulations and full scale tests to know which OOI can be properly monitored with an ROV.

As long as the offshore development keep moving further down in the deep sea, the use of UUVs in imaging of OOIs become more and more important.

## 3.2 Control Strategies

When taking images of an OOI the ideal situation would be to have a stationary platform to achieve quality images. This is however very challenging to implement everywhere. The alternative of using an ROV provides more flexibility as the platform is mobile. Because of the mobility, it is important to have good control strategies when navigating the ROV. For investigating an OOI, the two suggested solutions are to either use a form of DP control, or control the ROV with a joystick. These can also be combined such that the joystick control is used when moving around, while DP provides station-keeping. The focus is in this thesis will be on the joystick control.

### 3.2.1 DP Control

A DP vessel is [DNV, 2011]:
*Dynamically positioned vessel (DP vessel): A vessel which automatically maintains its position and heading (fixed location or predetermined track) exclusively by means of thruster force.*

In DP, the control system will stabilise the ROV on the desired position while the UW imaging process takes place. The mobility of the ROV makes it possible to gather images from several angles of the OOI.

The AUR-lab at NTNU has already developed a DP control system for ROV Minerva. This has provided good results, with position errors in surge and sway around 0.2-0.3 meters for station-keeping. The development and tests are presented in Kirkeby [2010].

The DP control system is sensitive to environmental forces, and in particularly currents. A disadvantage with a DP control system is that it will not be able to provide the same good results as a stationary lander would. For the purpose of taking some quick pictures of an OOI it could however provide good results if some error is allowed on the required accuracy. Another important aspect to consider is that the location and surroundings of the OOI might not be known in advance, and therefore the operator has to adjust the DP control system during the operation to encounter the possible unknown variables.

The analysis done in the project thesis it showed that the DP system cannot replace a stationary platform. It can still work as a valuable resource when only a ROV is available to take images of an OOI as long as some error is still allowed on the station-keeping [Lohne, 2012].

### 3.2.2 Joystick Control

With traditional joystick control an operator will control the propeller speed of each thruster on the ROV. This requires practice and is mostly suited for situations that do not require a high level of precision. Identifying the OOI, deciding the desired trajectory, and at the same time keeping the ROV in station-keeping would require a highly skilled and concentrated pilot. To perform such an operation is close to impossible, and this would be a server limitation on the operation window due to lack of available ROV operators.

One way to solve this is to implement the joystick as the reference generator instead of directly controlling the rotational speed of the thrusters. This idea is based on the concepts suggested by Dukan and Sørensen [2012] where the joystick generates the desired position and velocities. In this case the control system compensates for the environmental forces, and the operator can focus on getting into the correct position for taking images.

This type of joystick control system can be used in short term objectives to check an OOI from all sides, as well as investigating unknown areas. To further expand on how the objectives can be completed; some scenarios are presented where the joystick control methods can be a valuable resource.

- Scenario 1 - Full-stop
    - When investigating new and unknown areas, it is important to stop the ROV as fast as possible. As the visibility many places are low, the vehicle can be very close to an object before it is visible.
- Scenario 2 - Circle
    - A circle as seen in Figure 3.1. As the figure shows, the the ROV will move in a circle around the OOI, either closely followed by a constant speed, or trying to stay close to the desired position of the circle.
- Scenario 3 - Path
    - Another alternative is demonstrated in Figure 3.2. This is a combination where the ROV approaches from afar before moving in a circular

pattern. Then before completing the circle, the ROV will turn and head back towards the origin. This can typically be used in a case where the area is unknown from before, and therefore sets certain requirements to the control of the ROV in the sense of being able to stop fast when being close to the OOI, and easily go from a straight line movement to a circular movement.

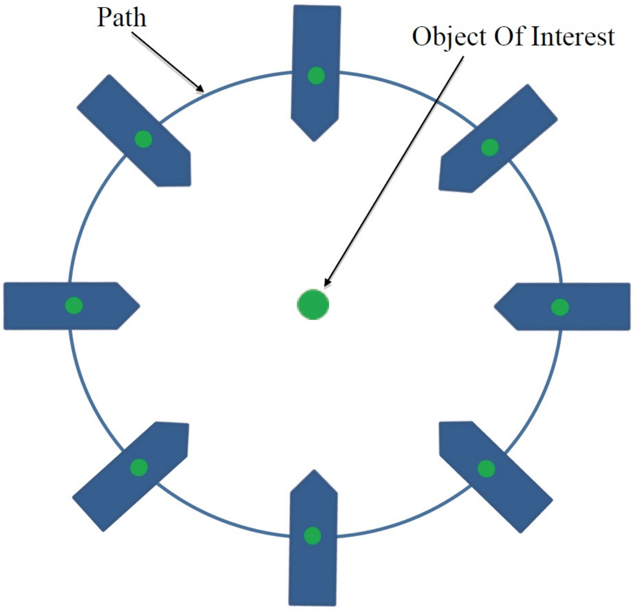


Figure 3.1: Joystick control where the ROV is moving in a circular pattern.

This way of using the joystick as a reference might have a big potential within UW imaging. This might be a challenge if the OOI is close to the seabed and the thrusters swirl up dirt from the seabed. The concept of using a joystick will be further expanded in different joystick control methods. These methods can be used to navigate the ROV in the different scenarios to get a better understanding of the strengths and limitations for each method.

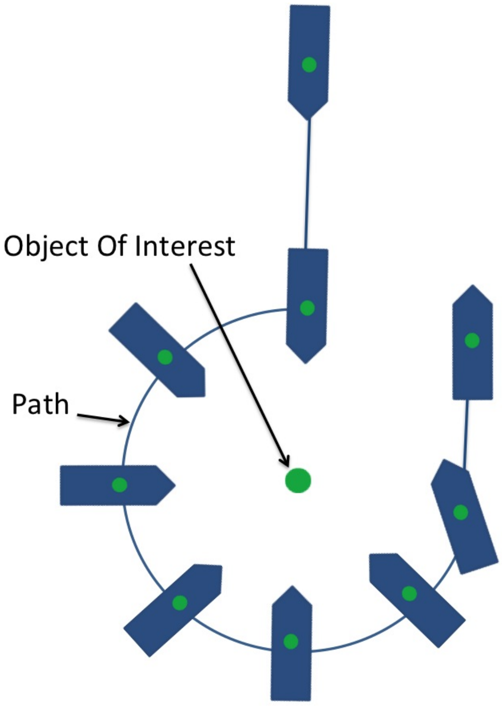


Figure 3.2: Joystick control where the ROV is approaching the OOI and then moving in a circle.

## 3.3 Joystick Control Methods

Different solutions are required to make use of the joystick directly or as a reference generator. The configurations have some similarities and differences. The main joystick control methods are direct thrust commands, velocity control method and position control method. These can all be used to fulfil the scenarios, but will have different control objectives and handling properties.

The first option is a link from the joystick module directly to the desired thrust of the ROV as seen in Figure 3.3. The ROV then produces a velocity $\nu$ and position $\eta$. The velocity $\nu^p$ is the perceived velocity by the ROV pilot, which then gives a new joystick command, $\nu^{p-js}$ , based on the visual feedback. This is sent to the joystick module through the joystick. This type of control is defined as open control loop with pilot feedback and input. Even though it is a closed loop in the figure, the term 'Open Control Loop' refer to the fact that there is no closed-loop control in this scenario, but only human-in-loop.

The alternative approach is to include a control system as seen in Figure 3.4. In this scenario the joystick module can produce a desired velocity $\nu_d$ or a desired position $\eta_d$ that is used as an input to a closed-loop control. The controller will try to minimize the error between the desired values and the actual values given by the ROV. As before there is still a pilot that perceives a velocity $\nu^p$. However the pilot will not give a direct thrust commands to the ROV, but the joystick works as a reference generator. One challenge with this approach is that the pilot might be unexpected and sudden joystick movements from the pilot, and it is therefore necessary to use a velocity reference model to generate a smooth reference value.

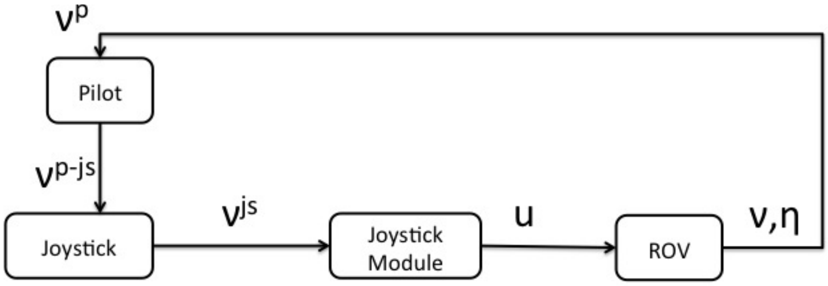


Figure 3.3: Block diagram showing the open control loop with pilot feedback and input.

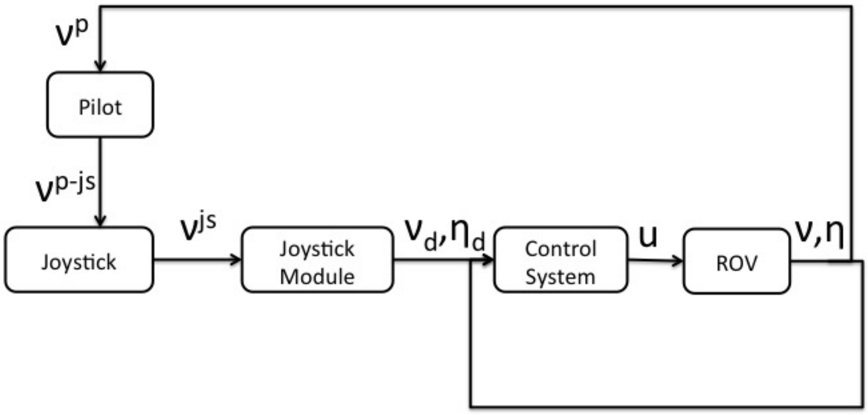


Figure 3.4: Block diagram showing the closed-loop control with pilot feedback and input.

Based on the two different block diagrams there are three main joystick control methods the pilot can use to control the ROV.

- Thrust commands
  - The joystick will be directly related to the desired RPM, $u$, of the ROV. This type of control is the most typical, and is also the standard configuration used by ROV pilots. It does not counteract for any environmental disturbances, and the pilot is required to steer the ROV and at the same time counteract any current or other disturbances on the movement of the ROV.
- Velocity control
  - The joystick commands are related to a desired velocity $\nu_d$ which is given as input to a velocity controller. This will try to keep the velocity of the ROV as close to the desired velocity as possible.
- Position control
  - The alternative to velocity control is to relate the joystick commands to $\nu_d$, and use integration to calculate the desired position $\eta_d$. It is not practical to relate the joystick directly to the desired position because the movement of the stick is too limited. The desired position can then be given as input to a position controller.

In all the methods there exists a human in the loop which decides the actions to be taken. There are no pre-generated way-points or implemented guidance system to decide the path of the ROV. The biggest difference between the methods is that the thrust commands relates the joystick commands directly to the ROV, while the velocity/position methods uses the joystick as a reference generator.

The overview of the different joystick control methods are listed in Table 3.1.

| **Joystick Control Method** | **Type** | **Ref. Model** | **Output** | **Joystick function** |
|---|---|---|---|---|
| Thrust | Open-loop | None | u | Direct |
| Velocity | Closed-loop | Velocity Reference Model | $\nu_d$ | Reference generator |
| Position | Closed-loop | Velocity Reference Model | $\eta_d$ | Reference generator |

Table 3.1: Overview of the joystick control methods and properties.

## 3.4 Control Structure Overview

The joystick can be used to all the states (surge, sway, heave and yaw) of the ROV. It can also be combined with other types of control to further expand the possibilities. There are many different configurations that can be used, but the focus in this thesis will be to explain some of the most common types. This is based on empirical data and previous work on the ROV Minerva control system. The categories we divide the control regimes into are:

- Automatic
    - Automatic control methods are those that require no human interaction in the system when it is running. There is a predefined path, an objective or a specific set-point given to the system. Based on the given data the vehicle will be controlled by a closed-loop controller.
- Manual
    - In a manual control method there is a pilot with the full control of the vehicle. The commands given correspond to an immediate change of the vehicle. The pilot needs to counteract any environmental disturbances.
- Semi-automatic
    - Semi-automatic control is a combination of automatic and manual control. One or more DOF can be fully automatic while others are manual. There can also be a form of indirect control where the human in loop continuously provides desired references that are handled by a control system.

Based on the categories we can look into different control objectives. In Table 3.2 the main methods are given. These are based on a complete overview that can be found in Appendix C. There is a division for each DOF depending on how it is controlled. The letters explain what desired value the controller type will try to maintain.

The letters in Table 3.2 symbolises:
S - Set-point, the objective is to keep the desired set-point.
T - Thrust, directly controlling the desired thrust.
V - Velocity, the objective is to keep the desired velocity.
P - Position, the objective is to keep the desired position.

| **Control Method** | **DOFs** | | | | **Category** |
|---|---|---|---|---|---|
| | Surge | Sway | Heave | Yaw | |
| **DP** | S | S | S | S | Automatic |
| **Thrust Commands** | T | T | T | T | Manual |
| with auto depth | T | T | S | T | Semi-Automatic |
| with auto depth & heading | T | T | S | S | |
| **Joystick Velocity Control** | V | V | V | V | Semi-Automatic |
| with auto depth | V | V | S | V | |
| with auto depth & heading | V | V | S | S | |
| **Joystick Position Control** | P | P | P | P | Semi-Automatic |
| with auto depth | P | P | S | P | |
| with auto depth & heading | P | P | S | S | |
| **Joystick Combination Control** | V | V | P | P | Semi-Automatic |
| with auto depth | V | V | S | P | |

Table 3.2: Overview of the different control objectives and alternatives.

# Chapter 4

# Modeling and System Setup

In order to implement joystick control there is a need for a model of the ROV and how to relate the vehicle to the joystick. This chapter presents the models, control design and the joystick simulation system.

## 4.1 Model of the ROV Minerva

The model of the dynamics for ROV Minerva can be divided in two parts. The kinematics describes the geometrical aspect of the motions, while the kinetics analyses the forces causing the motions.

### 4.1.1 Kinematics

When modelling the ROV we have 6 Degrees of Freedom (DOF), and according to Fossen [2011] they can be presented on the SNAME formulation as shown in Table 4.1.

| **DOF** | | **Linear and angular velocities** | **Positions and Euler angles** |
|---|---|---|---|
| 1 | Motions in x-direction (Surge) | u | x |
| 2 | Motions in y-direction (Sway) | v | y |
| 3 | Motions in z-direction (Heave) | w | z |
| 4 | Rotation about the x-axis (Roll) | p | $\phi$ |
| 5 | Rotation about the y-axis (Pitch) | q | $\theta$ |
| 6 | Rotation about the z-axis (Yaw) | r | $\psi$ |

Table 4.1: The SNAME notations for marine vessels

The position/rotation vector is given by

$$\eta = [x, y, z, \phi, \theta, \psi]^T \tag{4.1}$$

while the velocities are given by the vector

$$\nu = [u, v, r, p, q, r]^T \tag{4.2}$$

The reference frames that are typically used when analysing the motions of the ROV are NED and body. When relating the ROV motions to a joystick these frames are used, and a third frame, cylinder-coordinates, is also of interest.

- NED-frame
    - The reference frame called North-East-Down (NED) is the frame that will be considered as the inertial reference frame. It is earth fixed and has the name because the x-axis points north, the y-axis points east, and the z-axis points down towards the center of the earth. The position/rotation vector $\eta$ is given in this frame.
    - When the pilot moves the stick forward on the joystick, the ROV will move north without changing heading, and to the east when the stick is moved sideways. Therefore this frame can be used when the ROV pilot is looking at an overview of the position, and a display for heading and depth.
- Body-frame
    - The body fixed reference frame is a moving reference frame fixed to the vehicle. The x-axis points forward on the vehicle, while the y-axis points to the starboard, and the z-axis points down. The velocities $\nu$ is given in this frame.
    - The ROV will move in the positive surge direction when the stick on the joystick is moved forward and in positive in sway when the stick is moved to the right. The heading is controlled by rotation of the stick. This frame is typically used when the pilot is looking at the live feed from the cameras mounted on the ROV as it gives the feeling of more direct control.

- Cylinder-frame
  - The cylinder-frame relates the joystick parameters to a reference in a cylinder coordinate system. This is typically defined as a distance/radius $\rho$ from an origin defined by the pilot, and angle $\theta$ given by the $x$ and $y$ position of the ROV.
  - When pushing the stick forward, the ROV the distance to the origin will decrease, while pushing the stick sideways will make the ROV move in a circle around the origin.

As $\eta$ and $\nu$ are given in two different reference frames, they can be related through the kinematic relation in equation (4.3).

$$\dot{\eta} = J(\eta)\nu \tag{4.3}$$

where

$$J(\eta) = \begin{bmatrix} R(\Theta) & 0_{3x3} \\ 0_{3x3} & T_{\Theta}(\Theta) \end{bmatrix} \tag{4.4}$$

with

$$\Theta = [\phi, \theta, \psi]^T \tag{4.5}$$

and where $R(\Theta)$ is the linear velocity transformation matrix, and $T_{\Theta}(\Theta)$ is the angular velocity transformation matrix. More details about these transformation matrices can be found in [Fossen, 2011].

### 4.1.2 Kinetics

The forces and moments acting on a marine vehicle are described in Fossen [2011]. The different forces acting on the vehicle can be divided into rigid-body forces, hydrodynamic forces and hydrostatic forces. A ROV will also be affected by forces from the umbilical cable that connects it to surface ship.

**Process Plant Model**

The Process Plant Model (PPM) gives the necessary detailed descriptions needed for running simulations [Sørensen, 2012]. From Kirkeby [2010] the following 6 DOF PPM for a ROV is given by

$$\begin{aligned} \dot{\eta} &= J(\eta)\nu & (4.6) \\ M\dot{\nu} + C_{RB}(\nu)\nu + C_A(\nu_r)\nu_r &+ D_L\nu_r + D_{NL}(\nu_r)\nu_r + g(\eta) = \tau_{cable} + \tau & (4.7) \end{aligned}$$

In this model $\eta$ and $\nu$ is defined as in equation (4.1) and (4.2), and $\nu_r$ is the relative velocity. In the kinetics, $M$ represents the mass of the vehicle, $C_{RB}$ and $C_A$ are the Coriolis forces, and $g(\eta)$ is the restoring force. $D_L$ is the linear damping, and $D_{NL}$ is the nonlinear quadratic damping. $\tau_{cable}$ are the forces working from the umbilical, and $\tau$ are the control forces used to control the ROV [Kirkeby, 2010].

### Control Plant Model

The Control Plant Model (CPM) is a simplified mathematical model of the system to be used for control design and stability analysis based on e.g. Lyapunov Stability and passivity [Sørensen, 2012]. In the CPM we define a control space in which the control objective is defined [Fossen, 2011]. For a ROV this is surge, sway, heave and yaw, as roll and pitch are assumed stable, and there are no actuators to control those DOF.

The 4 DOFs CPM model for the ROV is given by

$$\begin{aligned} \dot{\eta} &= J(\eta)\nu \\ \dot{b} &= -T_b^T b + E_b w \\ M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g &= J(\nu)^T b + \tau \end{aligned} \tag{4.8}$$

Since the workspace is only 4 DOF the transformation matrix can be reduced to

$$J(\eta) = \begin{bmatrix} cos(\psi) & -sin(\psi) & 0 & 0 \\ sin(\psi) & cos(\psi) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.9}$$

The bias is long varying forces and accounts for modeling errors and other environmental disturbances, and the force from the umbilical is included in the bias. The bias is calculated in the NED-frame based on a Markov model with $T_b$ as a diagonal matrix of bias time constants. $E_b$ is a diagonal scaling matrix, and $w$ is a zero-mean Gaussian white noise vector. The linear damping $D_l$ and nonlinear damping $D_{NL}$ is combined by $D = D_L + D_{NL}$. The CPM is used to make the non-linear PID control in the simulation system.

## 4.2 Joystick Setup and Reference Frames

The joystick needs 4 axes to match the control space of the ROV. Figure 4.1 shows the reference frames for the joystick and the ROV body frame. The arrows indicate the positive directions. The origin of the x and y axes on the joystick are in the basis of the stick, while the z-axis is fixed to the stick. The $w$ axis is a separate lever.

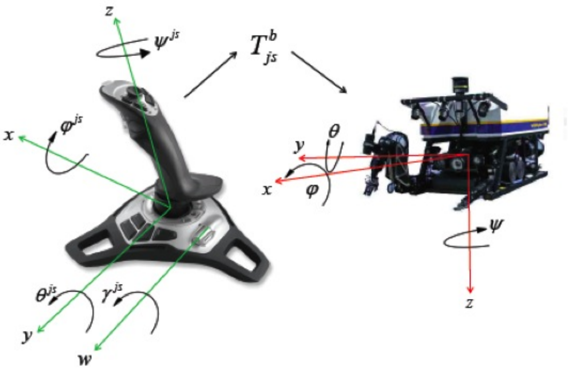


Figure 4.1: The Joystick and ROV reference frames [Dukan and Sørensen, 2012]

From the joystick we get the output vector

$$\Theta^{js} = \begin{bmatrix}\phi^{js} & \theta^{js} & \psi^{js} & \gamma^{js}\end{bmatrix}^T \tag{4.10}$$

where $\phi^{js}$ is rotation around the x-axis, $\theta^{js}$ is rotation around the y-axis, $\psi^{js}$ is rotation around the z-axis and $\gamma^{js}$ is the rotation of the lever around the $w$-axis.

The available actuation forces we have is given by

$$\tau = \begin{bmatrix}X & Y & Z & N\end{bmatrix}^T \tag{4.11}$$

where X,Y,Z are the forces in x,y and z direction, while N is the torque around the z-axis. The 4 DOF velocity vector for the ROV is given by

$$\nu = \begin{bmatrix}u & v & w & r\end{bmatrix}^T \tag{4.12}$$

The joystick output command $\Theta^{js}$ can now be related to a reference frame and the ROV dynamics. As it is not practical to relate the joystick commands directly to position, it is either related to thrust or velocity, given by $\tau^{js}$ and $\nu^{js}$. The direct output from the joystick is given in bits in the order $[-2^{15}\ 2^{15}]$, and is transformed to $[-100\ 100]$ for simplicity. The different methods of relating the joystick command to thrust or velocity are implemented with matrix operations.

### 4.2.1 Joystick to Thrust Commands

The joystick commands related directly to desired thrust is given by

$$\tau^{js} = K^{\tau}_{js} T^{b}_{js} \Theta^{js} \tag{4.13}$$

where

$$T^{b}_{js} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \end{bmatrix} \text{ and } K^{\tau}_{js} = \begin{bmatrix} K_X & 0 & 0 & 0 \\ 0 & K_Y & 0 & 0 \\ 0 & 0 & K_Z & 0 \\ 0 & 0 & 0 & K_N \end{bmatrix}$$

$T^{b}_{js}$ defines the connection between the joystick output and the desired thrust. Due to the z-axis on the joystick pointing upwards and the opposite on the ROV the elements $T^{b}_{js}(3,4)$ and $T^{b}_{js}(4,3)$ are negative to give a more intuitive feel of the control.

The matrix $K^{\tau}_{js}$ is a scaling matrix for the thrust, and is typically set to the max thrust capacities for the different directions. The values are previously found through tests done on ROV Minerva, and can be found in Appendix A.

### 4.2.2 Joystick to Desired Velocities

The desired velocities from the joystick commands are given by

$$\nu^{js} = K^{\nu}_{js} T^{b}_{js} \Theta^{js} \tag{4.14}$$

where

$$K^{\nu}_{js} = \begin{bmatrix} K_u & 0 & 0 & 0 \\ 0 & K_v & 0 & 0 \\ 0 & 0 & K_w & 0 \\ 0 & 0 & 0 & K_r \end{bmatrix}$$

Similar as for thrust, the scaling matrix $K^{\nu}_{js}$ defines the connection between the joystick output and the desired joystick velocities. It is important that $\nu^{js}$ is within the capabilities of the vehicle such that

$$max\{\Theta^{js}\} \Rightarrow max\{\nu^{js}\} \leq \nu_{lim} \tag{4.15}$$

where $\nu_{lim}$ is the max capacity for the vehicle velocity. As the joystick commands in equation (4.14) are given by a value between $-100$ and $100$, this can be achieved by setting

$$K^{\nu}_{js} = \nu_{max} \tag{4.16}$$

where $\nu_{max}$ is the max velocity for each DOF. The maximum velocities for ROV Minerva are previously found through full scale test and is listed in Appendix A.

## 4.3 Velocity Reference Model

The input $\nu^{js}$ might vary and be unpredictable depending on how the pilot uses the joystick. To ensure that the desired velocity is generating a reasonable value for the ROV to follow there is a need for a reference model. Different suggestions for a velocity reference model have previously been presented. A synthetic reference model which takes energy consumption into focus was implemented and tested [d. A. Fernandes et al., 2011]. This had some good results, but was not considered due to shortage of time. The one used in this thesis is from the work done by Dukan and Sørensen [2012] which is a filter-based reference model.

The 2nd order reference model can be found in Fossen [2011] and is given by equation (4.18), and the transformation to NED is given by equation (4.17).

$$\begin{aligned} \eta_d &= R(\psi)\nu_d && (4.17) \\ \ddot{\nu}_d + 2\Lambda\Omega\dot{\nu}_d + \Omega^2\nu_d &= \Omega^2\nu^{js}, && (4.18) \end{aligned}$$

where $\Lambda > 0$ and $\Omega > 0$ are design matrices for relative damping and frequencies. This model will assure that

$$\lim_{t\to\infty} \nu_d = \nu^{js}. \tag{4.19}$$

The velocity reference model is good when the pilot starts moving the ROV, and when keeping the joystick at a constant reference. Even though it takes some time to reach the desired velocity, this is not noticed as the pilot only sees the ROV moving and cannot tell from the visual feedback the exact velocity that was commanded. The challenge with the reference model is the slow deceleration to zero, when the joystick is back to initial position. In this case the ROV will keep moving for several seconds before coming to a complete stop [Dukan and Sørensen, 2012]. The consequence of the slow reaction might result in the pilot further moving the joystick in the opposite direction of the perceived velocity to stop it faster. This will result in a velocity being commanded and instead of stopping the ROV will start to move in the opposite direction. The result will be a fluctuating movement that can appear frustrating for the pilot.

To accommodate for the slow deceleration, a modification was proposed and implemented to test if it could improve the perceived feeling of control for the pilot. The new reference system is given by

$$\eta_d = R(\psi)\nu_d \tag{4.20}$$

$$\nu_d = \begin{cases} \ddot{\nu}_{d_i} + 2\Lambda_i\Omega_i\dot{\nu}_{d_i} + \Omega_i^2\nu_{d_i} = \Omega_i^2\nu_i^{js} & \text{if } \nu_i^{js} \neq 0, \\ \nu_{d_i} = \nu_{0_i}e^{-a_i(t-t_0)} & \text{if } \nu_i^{js} = 0 \text{ and } \mid \nu_i \mid > \nu_i^{tol}, \\ \nu_{d_i} = 0 & \text{if } \nu_i^{js} = 0 \text{ and } \mid \nu_i \mid \leq \nu_i^{tol}. \end{cases} \tag{4.21}$$

Where $\nu_i^{tol}$ is the tolerance limit for each DOF $i$, and tells when the velocity is low enough to switch to DP control. For the deceleration part, $\nu_{0_i}$ is the velocity at the time the joystick command becomes zero, $a_i$ sets the speed of deceleration, and $t_0$ is the initial time when the joystick command is set to zero and the deceleration starts.

The difference is quite big on the deceleration for the original and modified reference models as seen in Figure 4.2. This solution can therefore be an important aspect to make the pilot perceive a better control of the ROV.

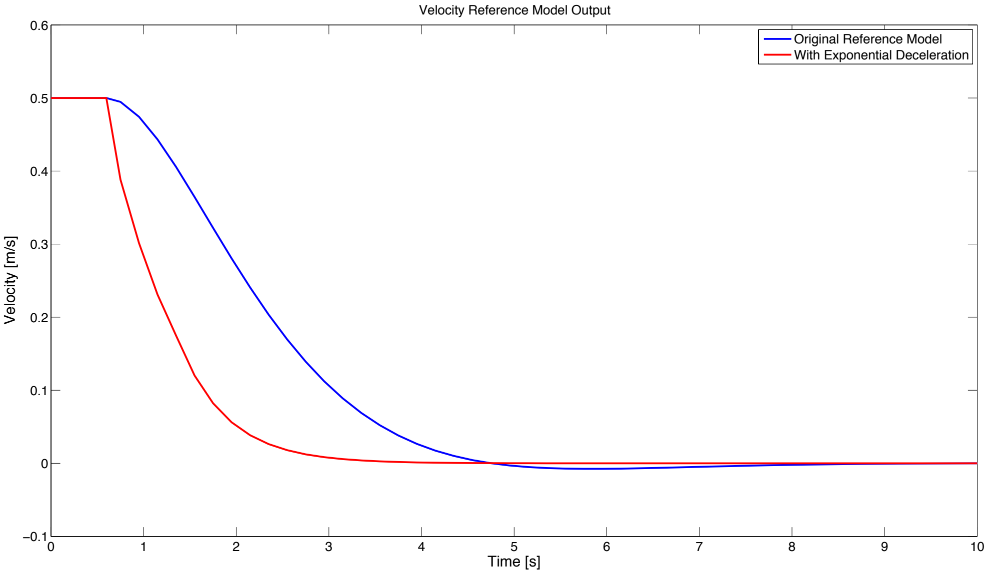


Figure 4.2: Response for the velocity reference model and the modified model.

## 4.4 Control Design

The closed-loop controller is based on the CPM found in equation (4.8). The controller is designed in several parts to achieve both position and velocity control.

The controller is developed by Kirkeby [2010], and further tested through the AUR-Lab.

### 4.4.1 Nonlinear PID Controller

The nonlinear PID control is found in Fossen [2011], and is used due to being robust and can easily be tuned [Kirkeby, 2010]. The control law is given as

$$\tau_{PID} = -J^{-T}(\eta)\left(K_p\tilde{\eta} + K_d\dot{\tilde{\eta}} + K_i\int_0^t \tilde{\eta}(\tau)d\tau\right) \tag{4.22}$$

Where $\tilde{\eta} = \eta - \eta_d$, $\dot{\tilde{\eta}} = \nu - \nu_d$ and $K_p$,$K_d$,$K_i = \mathbb{R}^{4x4}$ are diagonal gain matrices.

There is also a feedforward added to increase the tracking performance based on Sørensen [2012]. The feedforward is given by

$$\tau_{ff} = Ma_d + D(\nu_d)\nu_d + C(\nu_d)\nu_d \tag{4.23}$$

Where $a_d$ and $\nu_d$ is given by the reference system (4.21). The gravity and buoyancy are partly time varying and therefore not compensated for in the feedforward term.

The total control law will then become

$$\tau_{Non-PID} = \tau_{PID} + \tau_{ff} \tag{4.24}$$

For this controller there is also implemented an anti wind-up strategy. This is to avoid the effect called integrator wind-up. This can occur if the position/heading error is large over time and the integrator saturates one or more of the thrusters. The integrator will continue to integrate the large value, and when it is finally reduced it takes a lot of time to discharge the integrator value. The integral action including the anti wind-up strategy is given as

$$\tau_i = (K_i - K_{anti}(sat(\tau_i) - \tau_i))\int_0^t \tilde{\eta}(\tau)d\tau \tag{4.25}$$

Further details and implementation aspects can be found in Kirkeby [2010].

### 4.4.2 PI Controller

To control the velocity a PI controller was developed by the AUR-lab. The control law is given as

$$\tau_{PI} = K_{p\nu}\tilde{\nu} + K_{i\nu}\int_0^t \tilde{\nu}(\tau)d\tau \tag{4.26}$$

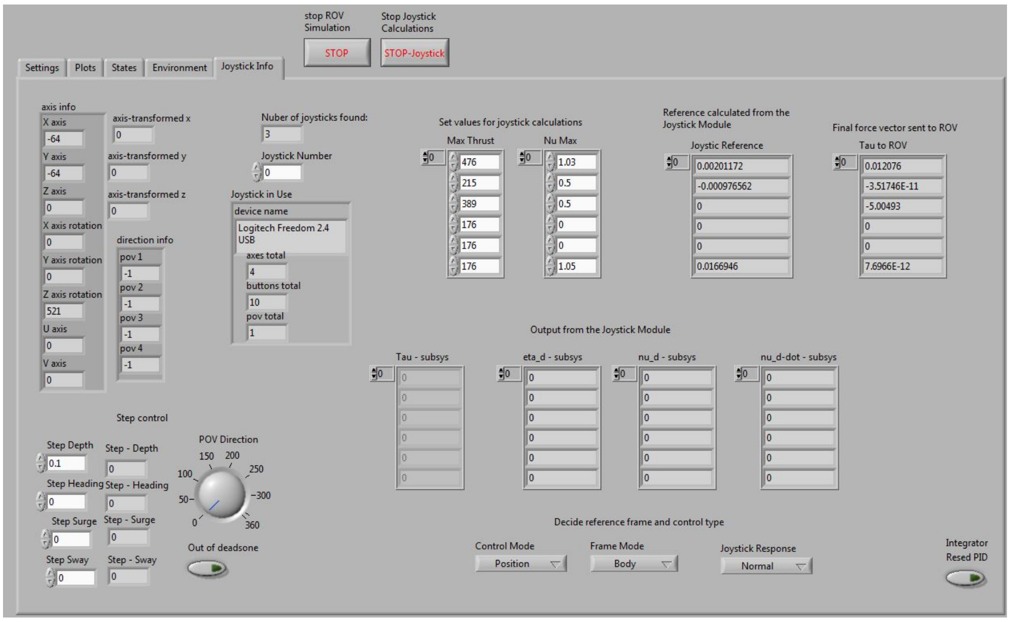
Where $\tilde{\nu} = \nu - \nu_d$ and $K_{p\nu}$,$K_{i\nu} = \mathbb{R}^{4x4}$ are diagonal gain matrices. The feedforward term in equation (4.23) is also included in this controller.

## 4.5 Joystick Simulation System

When there is a new feature or mode developed for the ROV control system it is tested through a Hardware-in-the-loop (HIL) test. This requires access to the physical control system. In order to test the joystick-ROV interaction without access to the HIL test system, a simplified simulation system was created. This simulation system is based on the fully developed control system, but only containing the necessary components to see how the joystick commands interact with the ROV. Currently it is based on the data and work done on ROV Minerva. The simulation system was developed in LabView, and can be used on any computer with this software installed. Of external hardware, it only requires a joystick to be connected to the computer running the simulation system.

The simulation system consists of 4 parts.

1. Joystick Connection
    - This part of the system is used to identify any joysticks that are connected to the computer and reads the commanded values. It uses a built in Virtual Instrument (VI) class found in LabView [Instruments, 2011].With this configuration it is possible to use any number of joysticks that are commercially available. In order to control all the 4 DOF on the ROV, it is important that the joystick consists of the same axis as described in section 4.2. The commanded values are normalized before they are sent to the joystick module.
2. Joystick Module
    - The joystick module is the main part of the system. Here the joystick commands are transformed to thrust or desired velocities depending on which control method that is selected. When the thrust option is chosen, the thrust commands are sent directly to the ROV simulator. If the preference is to control position or velocity the joystick module sends the desired velocity to the velocity reference system. Then either a desired velocity or desired position is generated depending on the selected control method.
    - LabView is a graphical programming language, and makes it easy to make an easy interaction panel for the system. Figure 4.3 is a screenshot of the Graphical User Interface (GUI) for connecting with the joystick. This panel is also used for deciding a control method and the user can see the inputs and outputs produced by the joystick and the joystick module.



axis info

X axis
-64
Y axis
-64
Z axis
0
X axis rotation
0
Y axis rotation
0
Z axis rotation
521
U axis
0
V axis
0

axis-transformed x
0
axis-transformed y
0
axis-transformed z
0

direction info

pov 1
-1
pov 2
-1
pov 3
-1
pov 4
-1

Nuber of joysticks found:
3
Joystick Number
0

Joystick in Use

device name
Logitech Freedom 2.4 USB
axes total
4
buttons total
10
pov total
1

Set values for joystick calculations

| Max Thrust | Nu Max |
|---|---|
| 476 | 1.03 |
| 215 | 0.5 |
| 389 | 0.5 |
| 176 | 0 |
| 176 | 0 |
| 176 | 1.05 |

Reference calculated from the Joystick Module

Joystic Reference
0.00201172
-0.000976562
0
0
0
0.0166946

Final force vector sent to ROV

Tau to ROV
0.012076
-3.51746E-11
-5.00493
0
0
7.6966E-12

Output from the Joystick Module

| Tau - subsys | eta_d - subsys | nu_d - subsys | nu_d-dot - subsys |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |

Step control

| Step Depth | Step - Depth |
|---|---|
| 0.1 | 0 |

| Step Heading | Step - Heading |
|---|---|
| 0 | 0 |

| Step Surge | Step - Surge |
|---|---|
| 0 | 0 |

| Step Sway | Step - Sway |
|---|---|
| 0 | 0 |

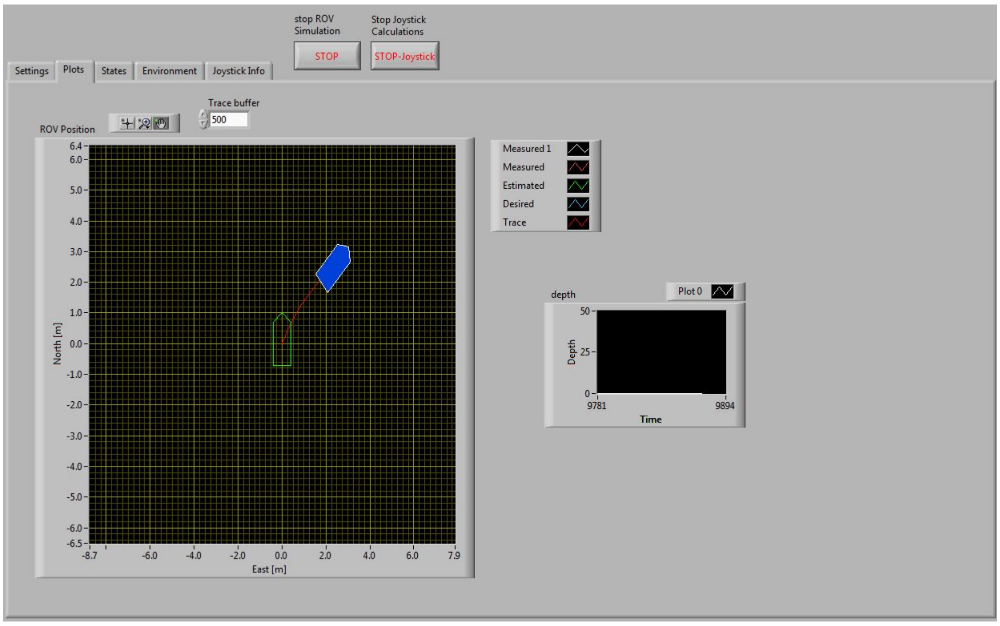
Decide reference frame and control type

Control Mode
Position
Frame Mode
Body
Joystick Response
Normal

Figure 4.3: The GUI for joystick options and control method.

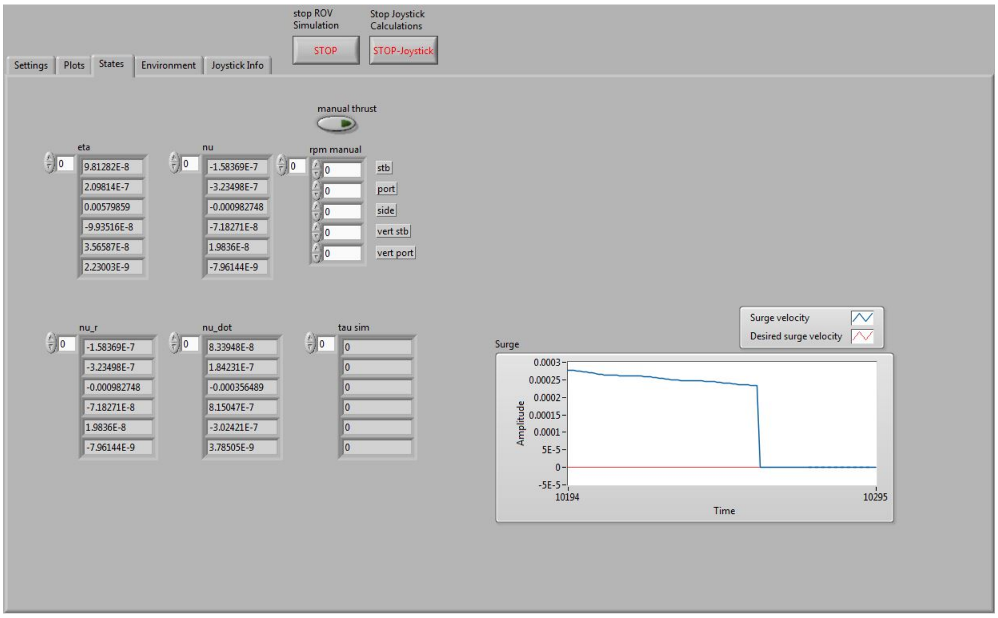
3. Closed-loop controller
   - The closed-loop controller is extracted from the full scale control system that is used by the AUR-Lab. It is based on the control design described in section 4.4. When position or velocity control is used, the closed-loop controller will output the desired thrust that is sent to the ROV simulator. This controller is only active when the joystick is used as a reference generator.
4. ROV Simulator
   - The ROV simulator simulates ROV Minerva based on the PPM in equation (4.6) and (4.7). As the focus is to look on joystick responses, the current system is simplified to assume full state feedback. Therefore the values of $\eta$ and $\nu$ produced by the ROV simulator are used as feedback in the control system. There are no further disturbances implemented. There is a feature implemented to make it possible to log the output data from the ROV simulation as well as the commanded joystick data. The data is stored in a text file for further processing.

- Figure 4.4 shows the GUI panel for following the path of the ROV. This gives an intuitive understanding of how the simulated ROV responds to the joystick commands given. This provides an easy simulation tool to further explore the connection between the ROV and the joystick.
- For a detailed update of the ROV states it is possible to use the GUI panel in Figure 4.5. These states can then be compared with the desired values in the joystick panel to ensure that the closed-loop controller is working properly. This panel also provides the opportunity to implement live graphs showing the different states and the desired value produced by the joystick.



Trace buffer 500

Figure 4.4: The GUI for following the movement and depth of the ROV.



| eta | nu | nu_r | nu_dot | tau sim |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 9.81282E-8 | -1.58369E-7 | -1.58369E-7 | 8.33948E-8 | 0 |
| 2.09814E-7 | -3.23498E-7 | -3.23498E-7 | 1.84231E-7 | 0 |
| 0.00579859 | -0.000982748 | -0.000982748 | -0.000356489 | 0 |
| -9.93516E-8 | -7.18271E-8 | -7.18271E-8 | 8.15047E-7 | 0 |
| 3.56587E-8 | 1.9836E-8 | 1.9836E-8 | -3.02421E-7 | 0 |
| 2.23003E-9 | -7.96144E-9 | -7.96144E-9 | 3.78505E-9 | 0 |

rpm manual: 0

| | rpm manual |
|---|---|
| stb | 0 |
| port | 0 |
| side | 0 |
| vert stb | 0 |
| vert port | 0 |

Figure 4.5: The GUI for detailed ROV states.

# Chapter 5

# Simulation of Joystick Control

Different scenarios for approaching an OOI using joystick control methods were presented in section 3.2.2. This chapter looks into the results from simulations of the scenarios to give the reader an opportunity to get an overview of the strengths and weaknesses of the different joystick control methods. These results are produced by the joystick simulation system, and demonstrate the value this system gives on analysing motions with joystick control.

The simulations were done using a Logitech Freedom 2.4 Cordless joystick. This is the same joystick that is used when doing live field experiments with ROV Minerva. All the simulations are done in the body-frame of the ROV. In operations the pilot typically uses the visual feedback from cameras on the ROV, and therefore the body-frame is the most commonly used. The focus of the simulations was horizontal movements, and heave is assumed controlled by auto depth.

## 5.1 Scenario 1 - Full-Stop

This scenario is used to analyse the difference between using thrust commands and the modified velocity reference model to come to a full-stop. Since the reference model is used in both position and velocity control, only the joystick velocity control method is presented.

### 5.1.1 Thrust Commands

Figure 5.1 shows the movement of the ROV with thrust commands. The ROV moves south before making it come to a full-stop. There is some unwanted heading movement when trying to get the vehicle to stop. The velocity development of the ROV can be seen in Figure 5.2. The surge velocity is accelerated to 0.8

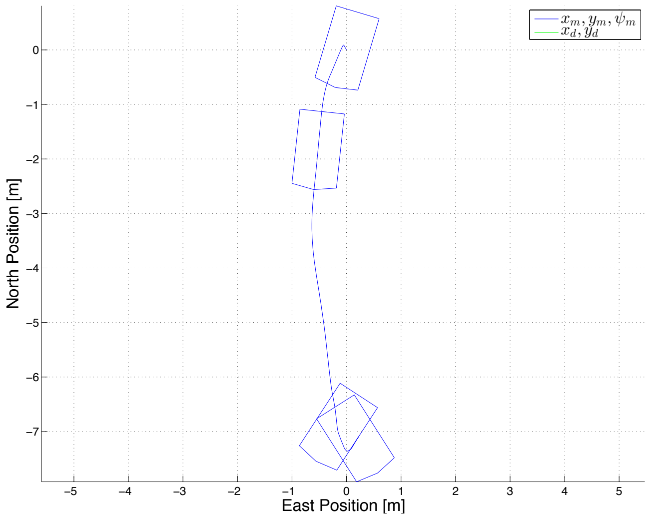


Figure 5.1: North-East plot of the ROV with direct thrust commands.

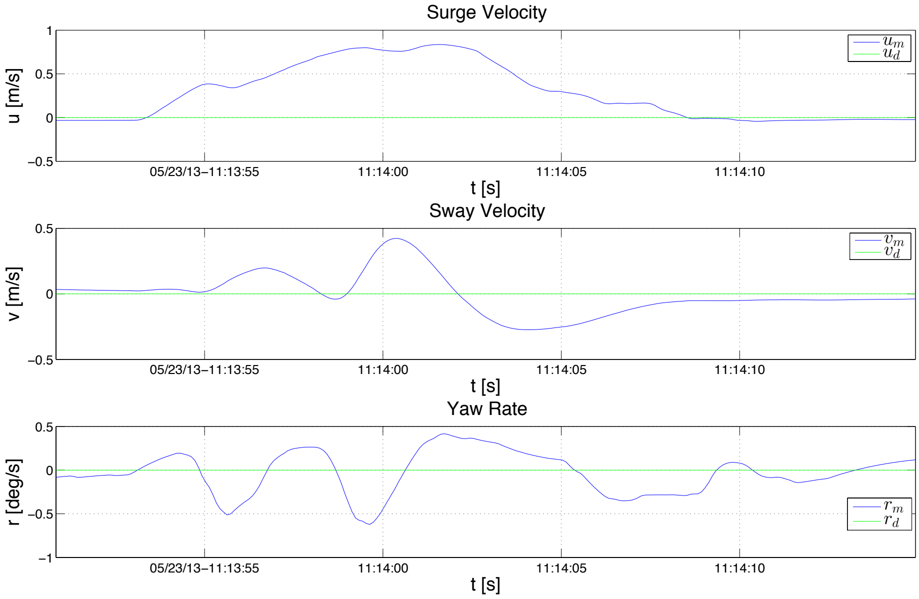


Figure 5.2: ROV horizontal velocities with direct thrust commands.

$m/s$ before trying to bring it back to zero. With manual control the process to achieve this consists of creating a negative thrust. As seen from the desired thrust in Figure 5.3, it is done through small jerks in the joystick. The ROV is brought to zero velocity, but it takes 6 seconds. It is possible to create a bigger thrust to slow down, but this can easily result in a big overshoot. During the process unwanted thrust is created in yaw which complicates the full-stop. Instead of only focusing on 1 DOF, the pilot needs to compensate for the yaw movements at the same time as slowing down the surge velocity.

Using thrust commands to stop the ROV is practical when wanting full control, but the results show that it requires some practice. Every small movement done with the joystick will result in thrust forces which makes the control challenging.

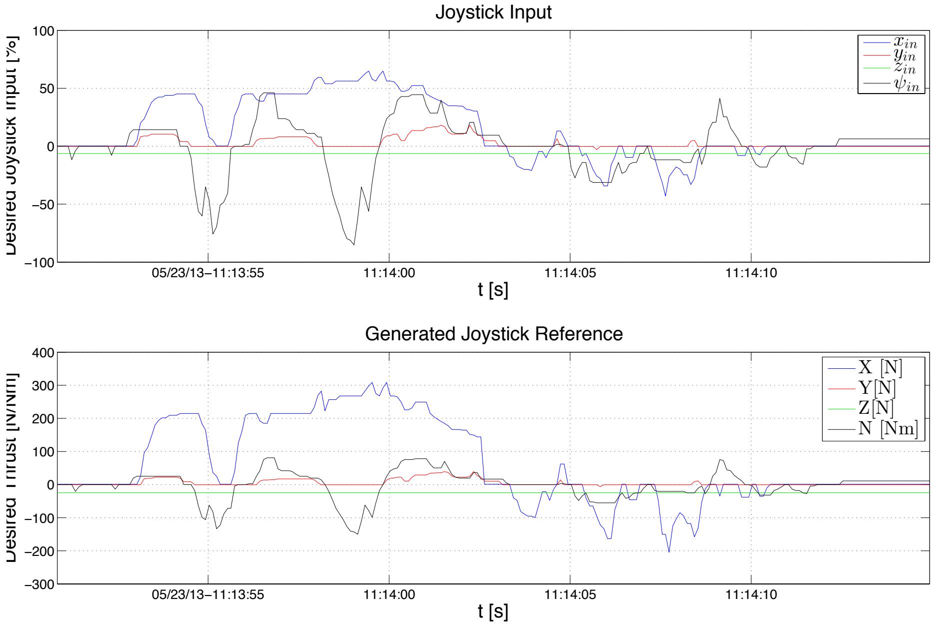


Figure 5.3: Joystick input and desired thrust with direct thrust commands.

## 5.1.2 Velocity Control

Figure 5.4 shows the movement of the ROV commanded with the velocity control method. In this case there is no unwanted heading movement when the ROV comes to a full-stop. The velocity profile of the ROV and the desired values can be seen in Figure 5.5. In the acceleration phase the surge velocity follows the desired velocity very closely, and the ROV reaches 1 $m/s$. There is some unwanted velocity created in sway and heave, but this is so small that it can be neglected.

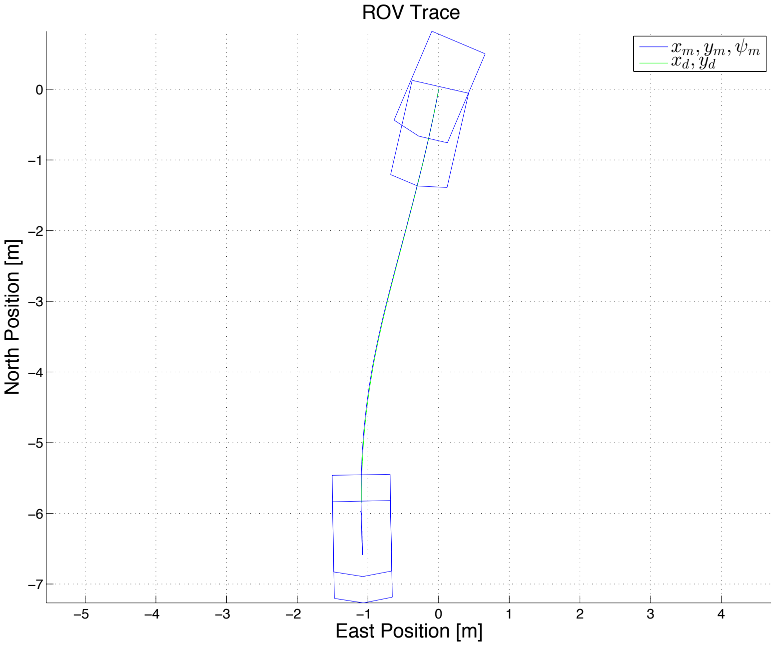


Figure 5.4: North-East plot of the ROV in velocity mode.

When the joystick is released the exponential deceleration takes effect. From Figure 5.6a we see that the joystick reference drops to zero. As seen in Figure 5.6b the thrust drops quickly, and as a result there is a rapid deceleration. The desired velocity in surge is quickly going to zero, but due to the inertia of the ROV there is a latency before the deceleration starts.

The reaction creates a small overshoot that results in the ROV moving backwards before reaching zero. As seen in Figure 5.4 there is around $0,5m$ unwanted movement backwards created by the rapid deceleration.

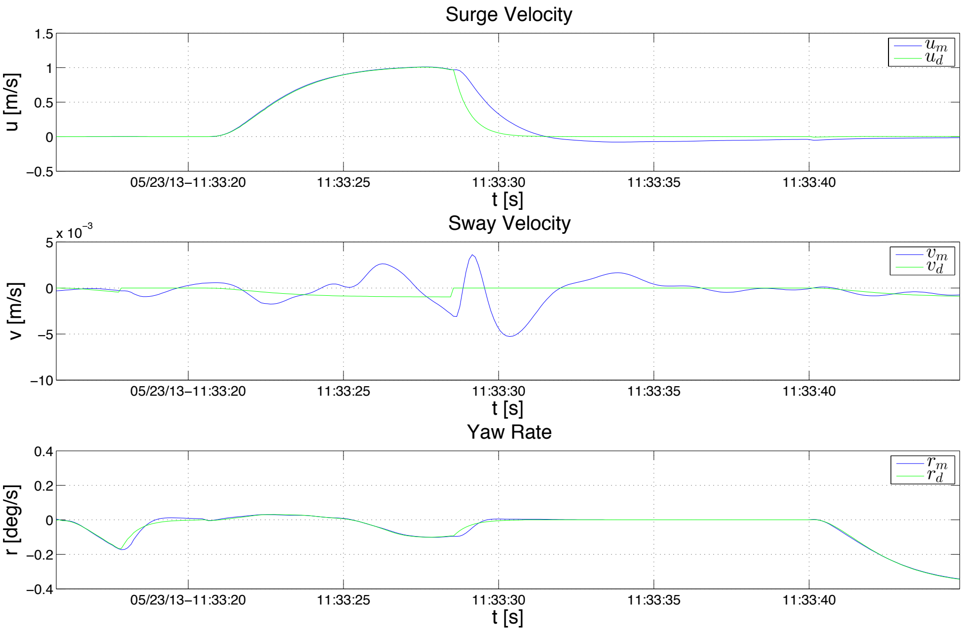
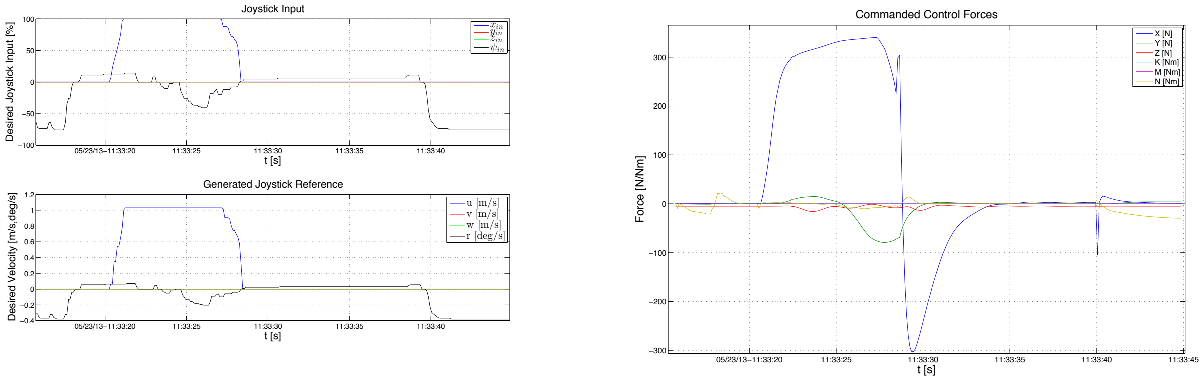


Figure 5.5: ROV horizontal velocities in with velocity control method.



(a) Generated joystick commands and desired velocities

(b) Generated desired thrusts commands

Figure 5.6: Joystick input and desired thrust for velocity control method.

### Summary of the full-stop simulations

In Table 5.1 the most important parameters for the two different control methods are mentioned. For both the cases there are some unwanted movements. The unwanted heading movement with thrust commands can be avoided, and will most likely decrease the more experienced the pilot is. The backwards motion in velocity mode needs might be reduced with further tuning of the closed-loop control, or changing the exponential deceleration in the velocity reference system.

The velocity control significantly reduces the time needed for stopping the ROV compared to direct thrust commands. The modified velocity reference model shows promising qualities for increasing the usability for the ROV pilots.

| **Parameters** | **Thrust Command** | **Velocity Control** |
|---|---|---|
| Initialisation | Manual joystick movements | Release the joystick |
| Reaches zero velocity | 6sec | 3sec |
| Unwanted movements | Heading (±30°) | Backwards motion $(0,5m)$ |
| Max Thrust Use | X (300 $N$)<br>N (150 $Nm$) | X (350 $N$)<br>N (30 $Nm$) |

Table 5.1: Comparison of full-stop motion for the different control methods

## 5.2 Scenario 2 - Circle

This scenario looks into the potential of moving around an OOI to view it from all sides. The heading needs to stay focused towards the center while having a sway velocity to move the ROV sideways. The radius of the circle is changed by moving closer or further away from the OOI. The simulations for the different methods are analysed according to how easy it is to keep the circular pattern, the thrust use and how big the fluctuations are in position and velocity.

### 5.2.1 Thrust Commands

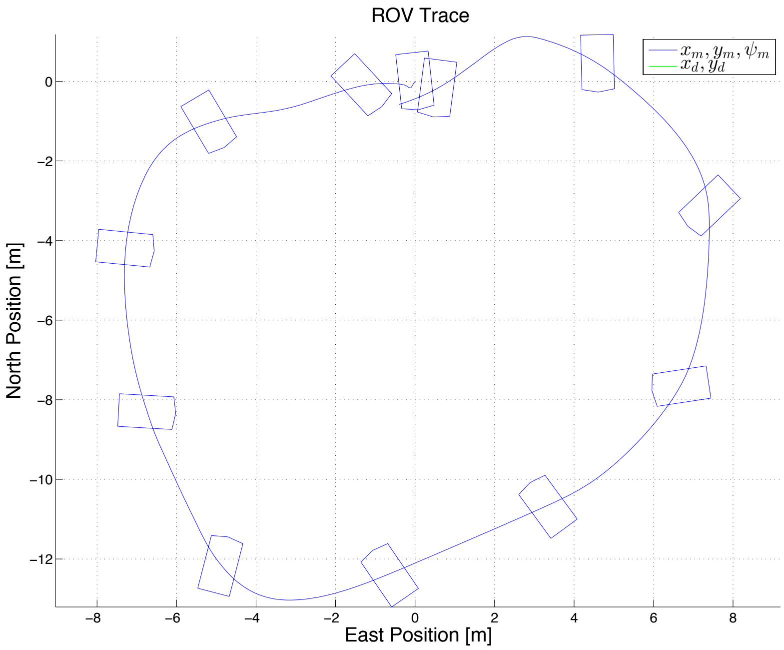


Figure 5.7: North-East plot of the ROV moving in a circle with direct thrust commands.

The circular movement of the ROV with thrust commands can be seen in Figure 5.7. The plot shows that the heading is moving back and forth instead of being directed towards the center of the circle. As a result the ROV is not moving in a even circular pattern.

The horizontal velocities are given in Figure 5.8. As the joystick is related directly to the desired thrust, the desired values are zero during the simulation. The velocities in surge are varying between 0.4 $m/s$ to $-0.5$ $m/s$ due to the constant compensation and trying to keep the circular pattern. The thrust in sway is stable while there are constant adjustments to yaw, as seen in Figure 5.9. The rapid adjustments cause a varying yaw rate and the circular pattern becomes uneven.

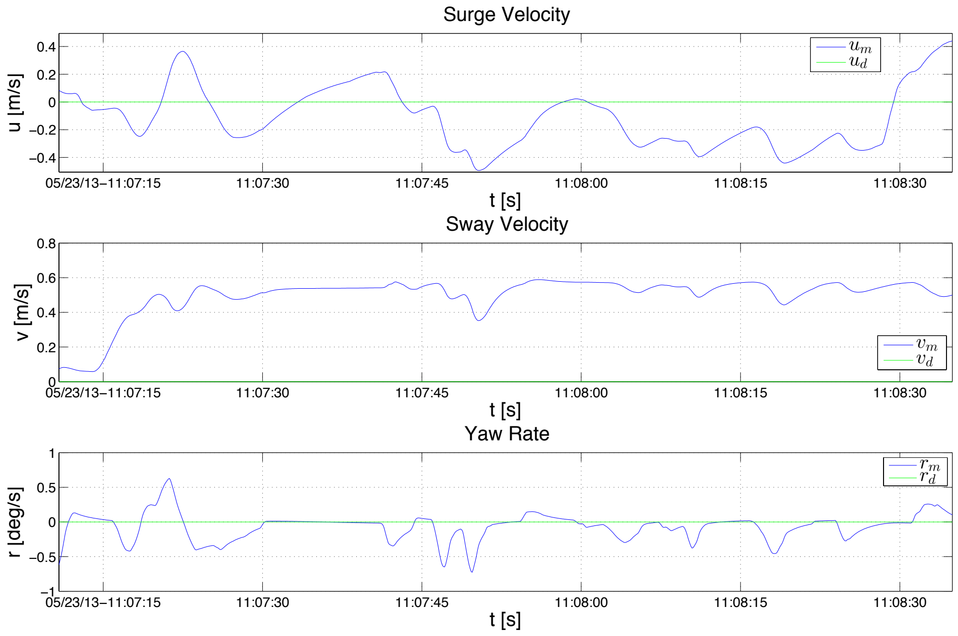


Figure 5.8: ROV horizontal velocities moving in a circle with direct thrust commands.

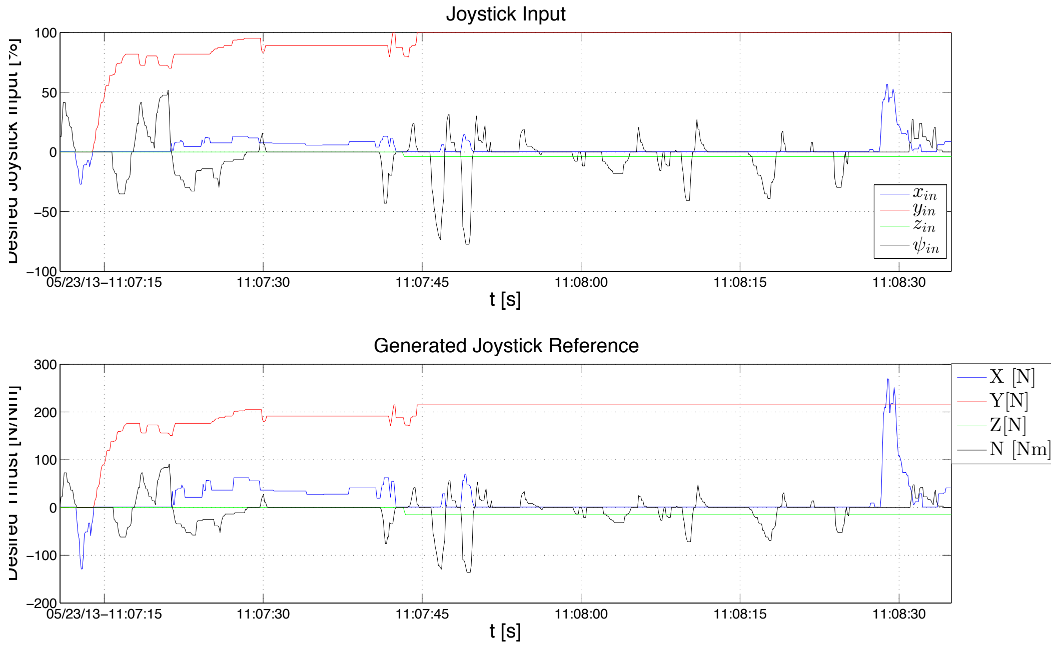


Figure 5.9: Joystick input and desired thrust with direct thrust commands

### 5.2.2 Position Control

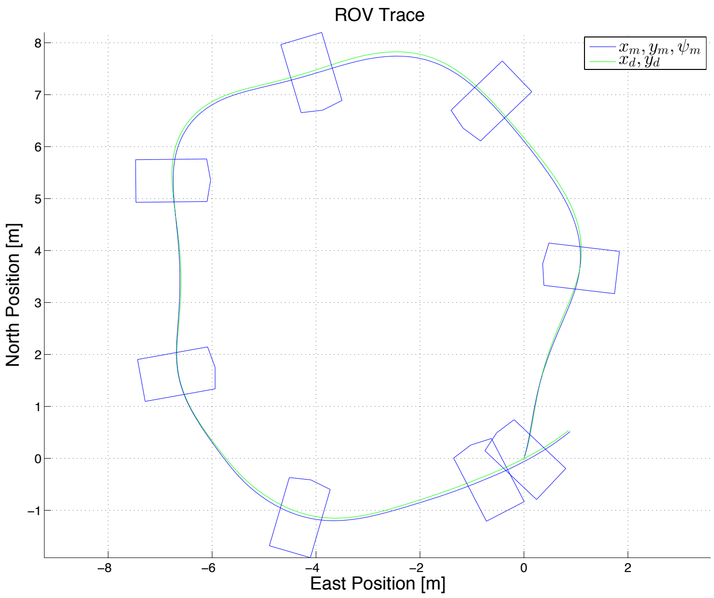


Figure 5.10: North-East plot of the ROV moving in a circle with position control method.

Figure 5.10 shows the movement of the ROV with the joystick position method. When the position control is used, the circular pattern is much better than in the case with thrust commands. The ROV is following the desired trajectory very closely with only a small error margin. From the plot we can see that the heading is not all the time pointing towards the center.

The horizontal velocities are given in Figure 5.11. Even though the closed-loop controller is focused on the position error the offset in the sway velocity is very small. There is a difference of $0,05$ $m/s$ between the desired and measured velocity. As this is a full state feedback simulation system, the variations will probably be more at the full scale tests.

In Figure 5.12a there is a big variation in the yaw joystick command to try to keep the turning coherent with the sway movement. This is related to the challenge of finding a yaw velocity that makes the heading change in the exact rate needed to make a complete circle. There is a thrust generated in surge from the control system as seen in Figure 5.12b. This is supporting the ROV to follow the desired position, and demonstrates the advantages of a closed-loop control compared to manual control.

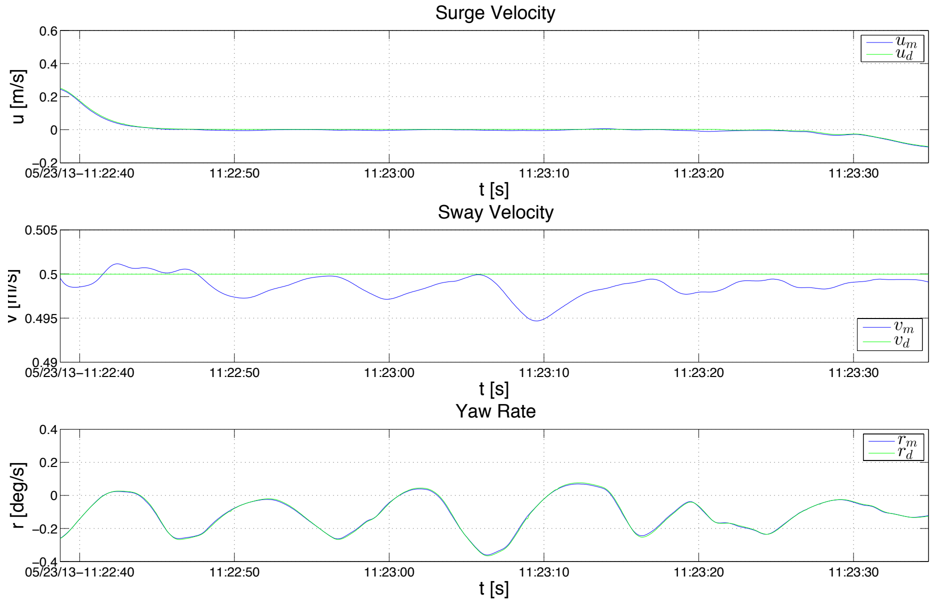
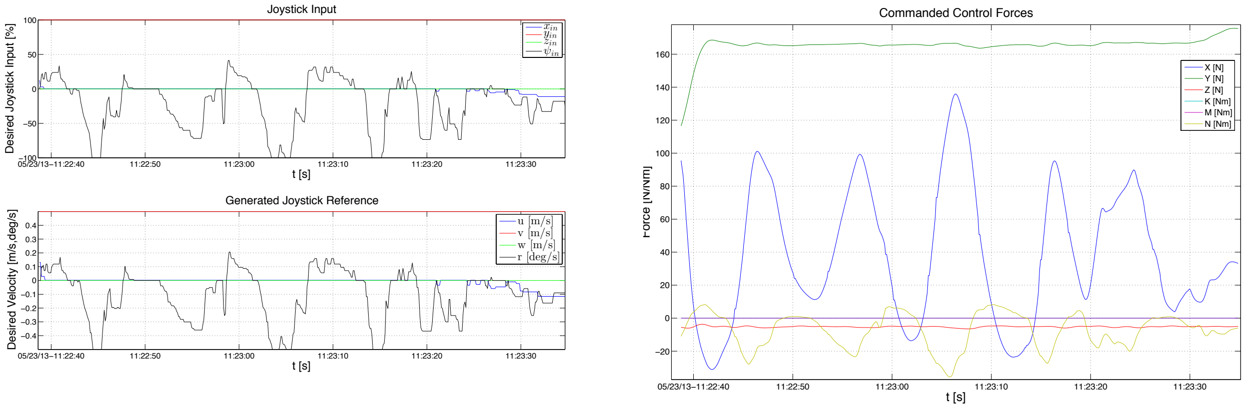


Figure 5.11: ROV horizontal velocities moving in a circle with position control method.



(a) Generated joystick input and desired velocities

(b) Generated desired thrust

Figure 5.12: Joystick input and desired thrust with position control method

### 5.2.3 Velocity Control

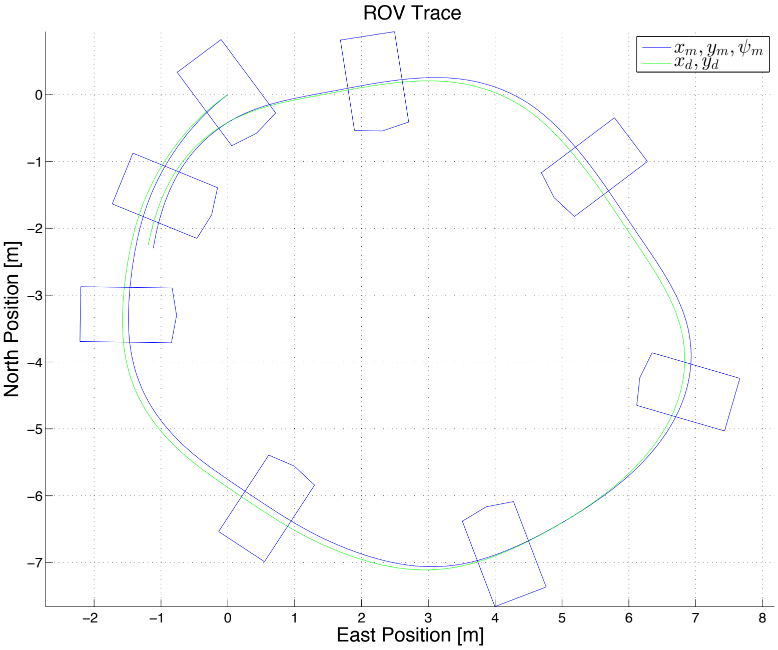


Figure 5.13: North-East plot of the ROV moving in a circle with velocity control method.

Figure 5.13 shows the ROV movement in a circular pattern using velocity control. The circular pattern is better than both the previous cases, with the heading focused towards the center. The difference is bigger between the measured and desired position as the focus is on limiting the velocity error.

The surge velocity error is so small that it can be neglected, as seen in Figure 5.14. There is no error on the sway velocity since the closed-loop controller is focusing on reducing the difference between measured and desired velocity. The smooth movement makes this method very suited for taking video or images with good quality.

The joystick input in Figure 5.15a shows that there is a big variation in the yaw input to keep the heading centred. Figure 5.15b shows that also in this case there is a thrust provided in surge from the closed-loop controller to try to satisfy the control objective.

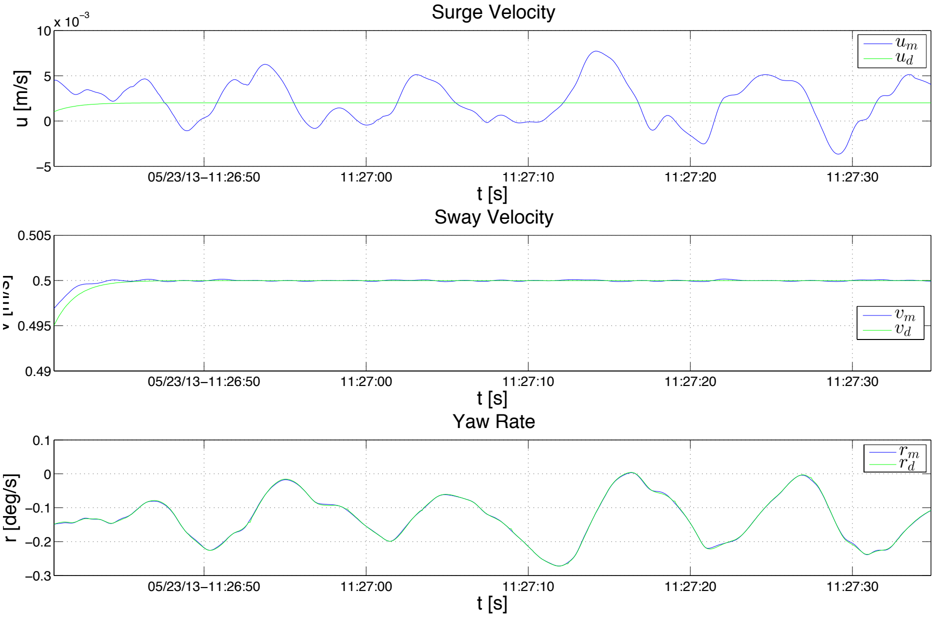
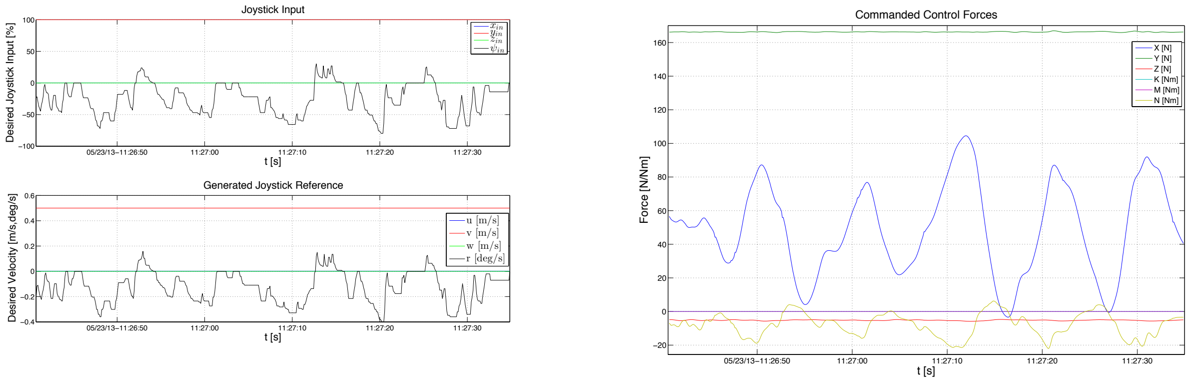


Figure 5.14: ROV horizontal velocities moving in a circle with velocity control method.



(a) Generated joystick input and desired velocities

(b) Generated desired thrust

Figure 5.15: Joystick input and desired thrust with velocity control method.

### Summary of the circular simulations

Table 5.2 shows a summary of the parameters for the different methods when trying to move in a circle. The thrust is the hardest mode to create a circular movement and requires most experience by the pilot to manage. The position method makes a good circular movement, but with the focus on the position error it can create variations in the velocity. If there is a need to stop during the circular movement and maintain the current desired position, this method can provide a good station-keeping.

The velocity method provides the best solution for taking images, because the velocity is kept close to constant during the circular movement. This method is also more economic on thrust during the simulation.

| **Parameters** | **Thrust Command** | **Position Control** | **Velocity Control** |
|---|---|---|---|
| Max Position Error | Uneven circle | 0.05 $m$ | 0.1 $m$ |
| Max Velocity Error | Big variations | 0.005 $m/s$) | 0.005 $m/s$ |
| Max Thrust Use | X (275 $N$)<br>Y (220 $N$) | X (136 $N$)<br>Y (175 $N$) | X (105 $N$)<br>Y (166 $N$) |

Table 5.2: Comparison of circular motion for the different control methods

## 5.3 Scenario 3 - Path

This scenario is useful to see if the methods provide good control when the area is unknown. If the visibility is poor the ROV needs to get close to the OOI, stop and then move around it to investigate. The simulations for the different control methods are analysed according to how well the ROV approaches the OOI, the change from straight line to circular movement, and how smooth the vehicle move around the OOI.

### 5.3.1 Thrust Commands

Figure 5.16 shows the movement of the ROV in the path when using thrust commands. When approaching the change from a straight line to the circular movement the path has the shape of sideways turn. Similar to the circle test the heading is not directed towards the center. Some improvement can be seen, because this simulation is done at a later point with more experience within joystick control.

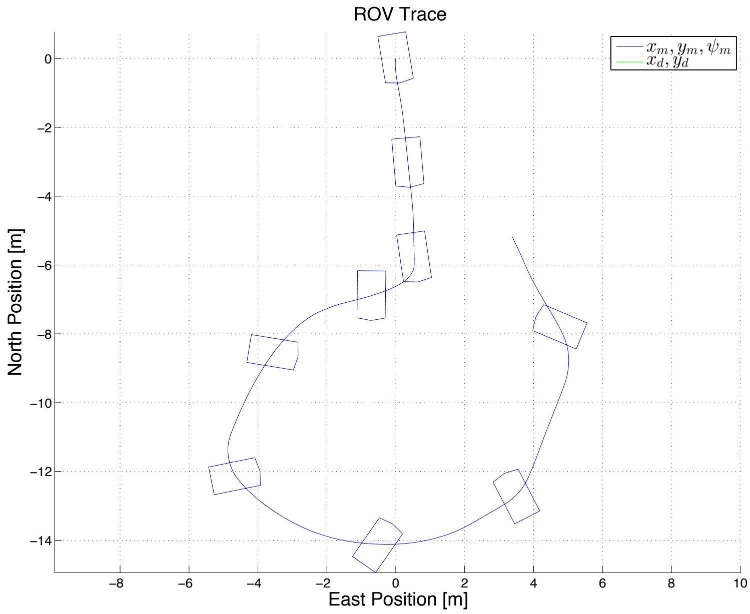


Figure 5.16: North-East plot of the ROV moving in a path with direct thrust commands.

There is a slow deceleration of the surge velocity, and this is occurring while the sway velocity is increased, as seen in Figure 5.17. This causes the ROV to move

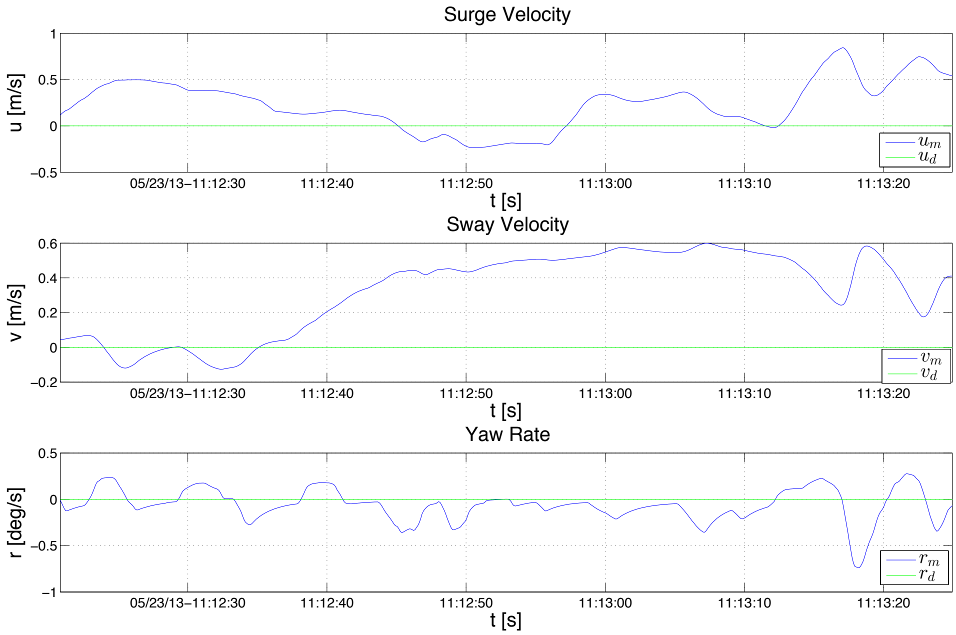


Figure 5.17: ROV horizontal velocities when moving in a path with direct thrust commands.

in the sideways turn instead of a clear change between the patterns. The yaw velocity is fluctuating around zero to try to keep the heading directed towards the center of the circular movement.

The joystick commands and generated desired thrust is given in Figure 5.18. A constantly changing joystick input is needed in order to make the ROV move in the planned path. This is not ideal for surveying as the generated thrust forces makes the velocities vary, and this can reduce the quality of the images and video recorded.

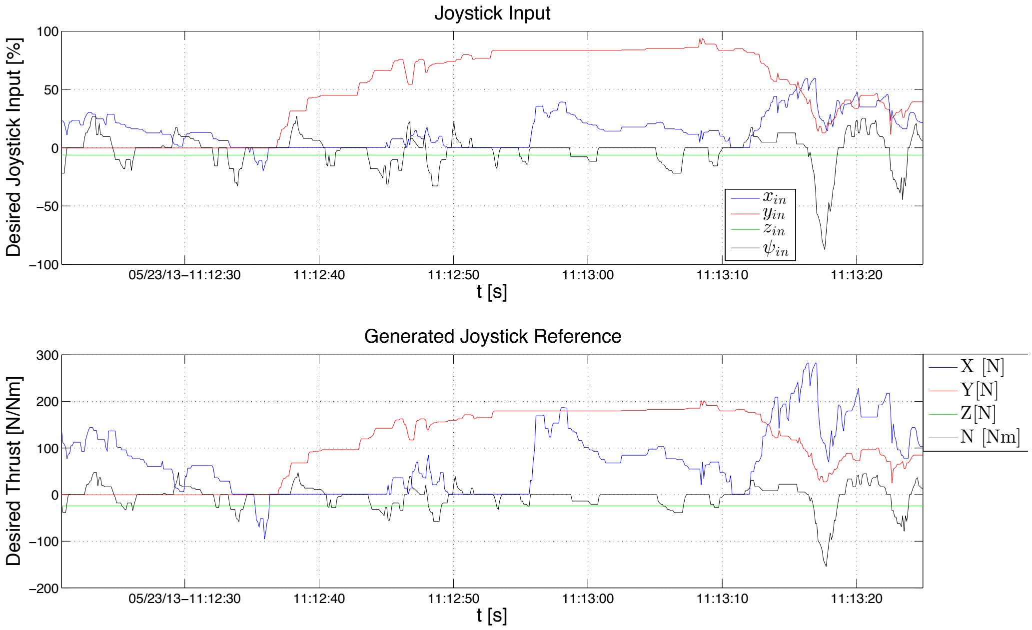


Figure 5.18: Joystick input and desired thrust with direct thrust commands.

### 5.3.2 Position Control

The path of the ROV in position control is seen in Figure 5.19. There is a full-stop before entering the circular movement. This makes it possible to survey the site before deciding the next course of action. The clear transition between the movements results in the heading being pointed towards the center of the circle, as well as a clearer circular pattern.

The horizontal velocities are presented in Figure 5.20. There is an overshoot of 0.1 $m/s$ in the surge velocity to compensate for the position error. The same occurs for the sway velocity in the end of the simulation. This results in a backwards movement of 0.15 meters when entering the full-stop motion.

The joystick commands, generated desired velocity and the thrust generated from the position controller is presented in Figure 5.21. The joystick input is also varying as in the case of the thrust commands, but the output of the joystick module is better due to the velocity reference model. In Figure 5.21b we see the two rapid thrust changes at 11:17:50 and 11:18:31 that appears due to the deceleration stage. Even though it changes fast, the generated thrust is still well within the maximum thrust capacity.

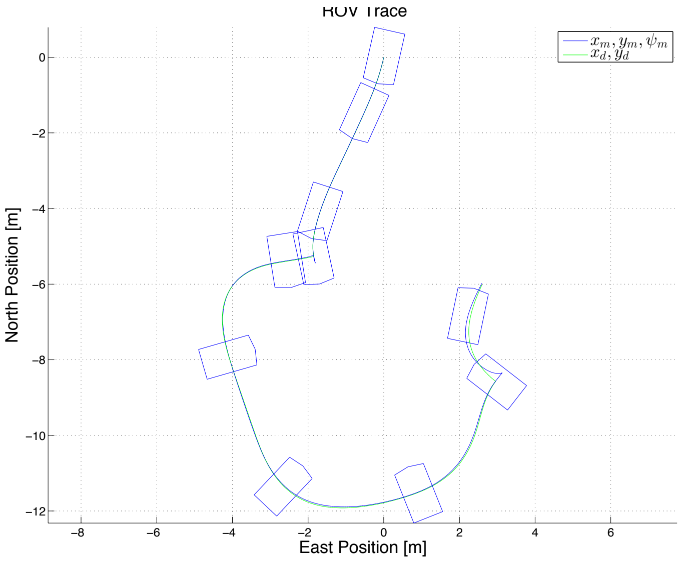


Figure 5.19: North-East plot of the ROV moving in a path with position control method.

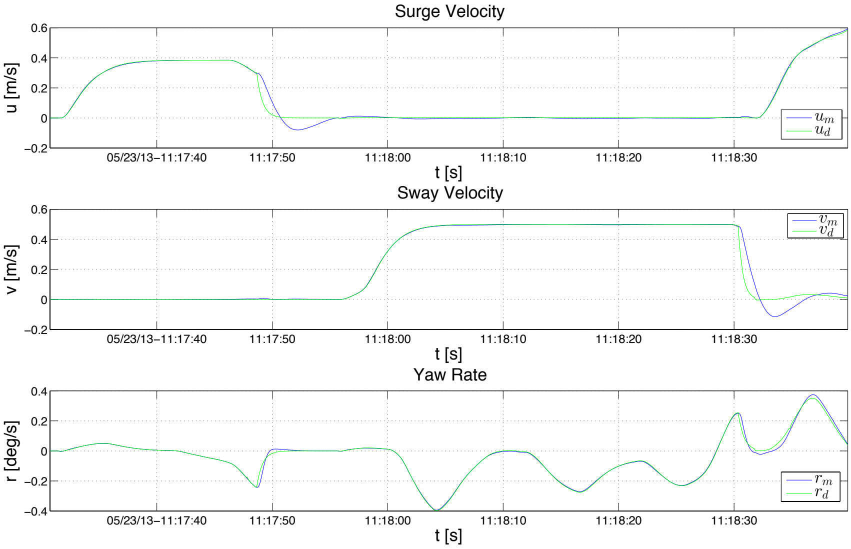
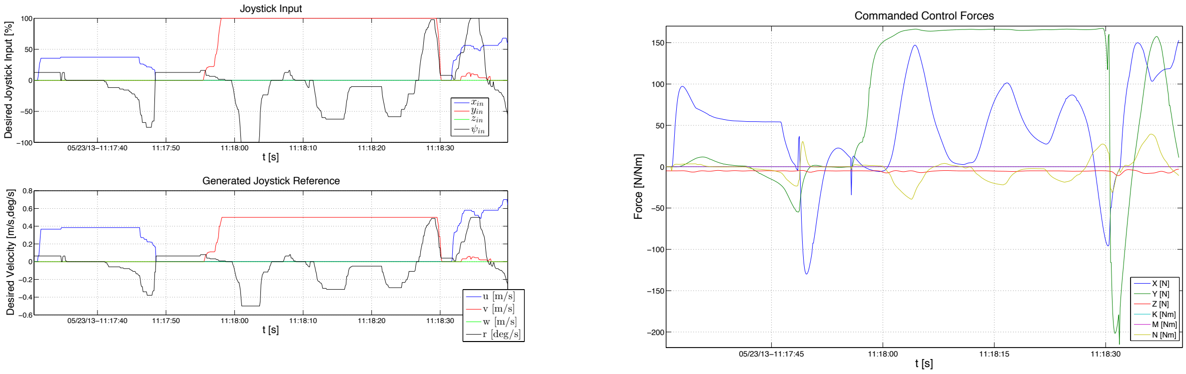


Figure 5.20: ROV horizontal velocities when moving in a path with position control method.



(a) Generated joystick input and desired velocities

(b) Generated desired thrust

Figure 5.21: Joystick intput and desired thrust with position control method.

### 5.3.3 Velocity Control

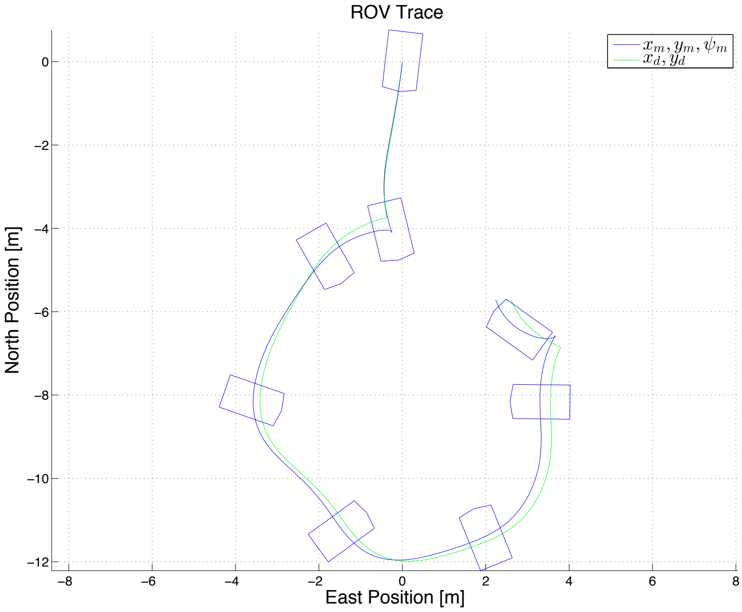


Figure 5.22: North-East plot of the ROV moving in a path with velocity control.

Figure 5.22 shows the movement of the ROV when using the velocity method to move in a path. The ROV follows the desired position on the straight line towards the OOI. The transformation from surge to sway velocity is without the backwards motion, due to allowing a bigger position error. During the circular movement, the position error increases to 0.15 meters. The heading follows the center of the circle most of the time, but with some more variations.

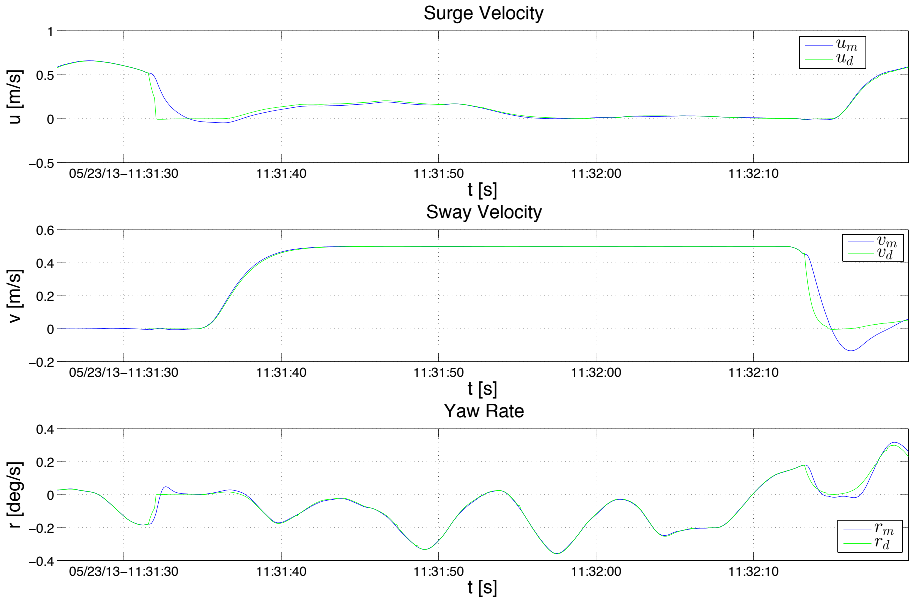
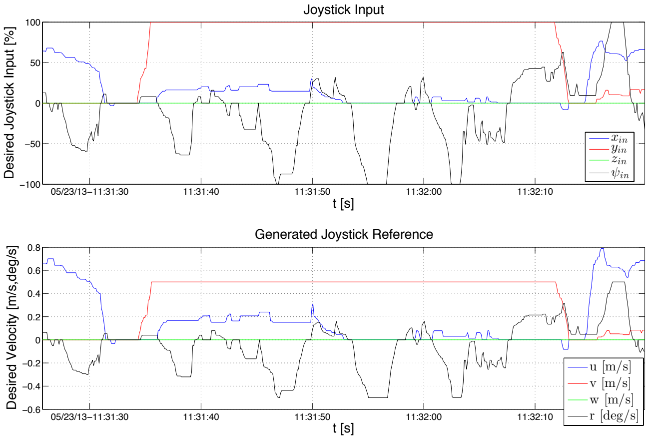
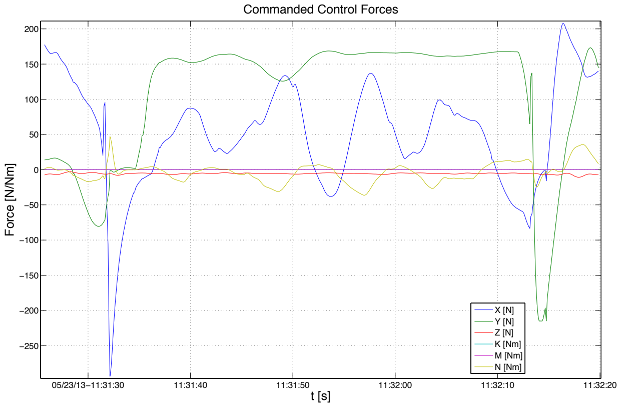


Figure 5.23: ROV horizontal velocities when moving in a path with velocity control method.

The ROV horizontal velocities can be seen in Figure 5.23, and the overshoot in surge velocity is small (0.05 $m/s$) when using this control method. The generated desired velocity based on the joystick input is seen in Figure 5.24a. The reference is very stable for desired velocity in sway, while surge and heave is used to compensate for moving away from the desired path. In Figure 5.24b there is also the rapid thrust changes needed to stop the ROV. They are more aggressive for this method then for the position control.



(a) Generated joystick input and desired velocities



(b) Generated desired thrust

Figure 5.24: Joystick input and desired thrust with velocity control method.

### Summary of the path simulations

Table 5.3 shows a summary of the parameters for the different methods when trying to follow a path. The manual control is the most difficult to use in this scenario as well, and once again demonstrates the dependency of an experienced pilot. The position control follows the desired path generated by the joystick input, but with a chance of more fluctuation in the velocity. There is also a bigger overshoot when commencing the full-stop, but this also provides a chance to get an overview of the area. The velocity control method demonstrates good qualities for keeping a stable velocity, but it requires more thruster capacity then the other two methods.

| **Parameters** | **Thrust Command** | **Position Control** | **Velocity Control** |
|---|---|---|---|
| Overshoot | Non to measure | North $(0,15\ m)$<br>East $(0,15\ m)$ | North $(0,35\ m)$<br>East $(0,25\ m)$ |
| Max Position Error | Non to measure | $0,03\ m$ | $0,15\ m$ |
| Max Velocity Error | None to measure | $0,02\ m/s$ | $0,02\ m/s$ |
| Max thrust use | X (125 $N$)<br>Y (200 $N$) | X (147 $N$)<br>Y (215 $N$) | X (293 $N$)<br>Y (215 $N$) |

Table 5.3: Comparison of path movement for the different control methods

## 5.4 Discussion of the Simulation Results

The simulations demonstrate different qualities for the joystick control methods. The results are very dependent on the experience of the pilot, and thus cannot be set as a standard. It can however give some indications of which control method to use for different operational objectives.

Thrust commands gives a direct control over the vehicle, but is also the most difficult to master. This requires a lot of practise and provides no support to compensate for environmental disturbances. This is therefore most suited when surveying and investigating new areas where there is no requirements to produce images or temporal coverage.

The position method is good for movement that also include station-keeping, and provides the pilot a chance to stop and get an overview before counting the surveying. When variations in the velocity are not important, this mode can be used to investigate OOIs that span over larger areas. This method also provides good results for full-stop motion that can be important to have in unknown areas with low visibility.

For taking UW images in a time series with a moving ROV, the best solution is to use the velocity method. This ensures a constant velocity during the movement, and demonstrates the best results with keeping the heading fixed towards one location.

Both the closed-loop control methods are easier to use by a less experienced ROV pilot. This might change when a pilot experienced with manual control switching over to a closed-loop joystick control method. This is important to take into consideration when deciding which method to use for the operation.

# Chapter 6

# Full Scale Experiments

Full scale experiments of the joystick control methods were conducted on the 10th of May. This was done outside the Trondheim Biological Station (TBS). Due to limited operation time and an unexpected challenge with the reference system, only some of the concepts were tested in full scale.

## 6.1 Implementation

The modules from the joystick simulation system were implemented in the full control system for ROV Minerva. This went through a HIL test on the 9th of May to ensure that everything was properly integrated. During the full scale experiments it was discovered that the desired position in heave changed when commands were given in surge. This was not discovered in the HIL tests, and made the full scale experiments come to some shortcomings.

Usually full scale experiments are performed from the NTNU research vessel (R/V) Gunnerus, but it was not available on the test day. Instead a new Long base line (LBL) positioning system had just been implemented outside TBS. The LBL system is a grid of transponders installed fixed on the seabed with known locations. The transponders are then communicating with the ROV to measure the current position. This system was not working upon arrival, and some configuration time was needed. The results from the tests show that the position reference dropped out from time to time, so parts of the testing was run in dead reckoning. The LBL position system also has quite some noise, and therefore the measured values are not presented in the North-East plots.

Due to the limited time, the focus was to gather results of a full-stop scenario and a path scenario. The main idea was to compare all the different joystick control methods, but only the thrust and position methods were tested within the available time. To make the tests similar to the simulations, heave was controlled by auto depth and the focus was on the horizontal states. The tests were conducted with the same joystick as in the simulations, and the author had the role as ROV pilot.

## 6.2 Full-Stop Results

Figure 6.1 shows the movement of the ROV in thrust mode. When trying to bring the ROV to a full-stop the heading turns 180°. The surge velocity is accelerated to $0,8m/s$ before trying to bring it back to zero as seen in Figure 6.2. The stopping motion creates a negative velocity, and when trying to compensate the velocity is increasing and becoming positive. During this process some yaw velocity is created, and trying to slow down the ROV and at the same time reduce the yaw rate is rather complicated and thus creating the unwanted turn.

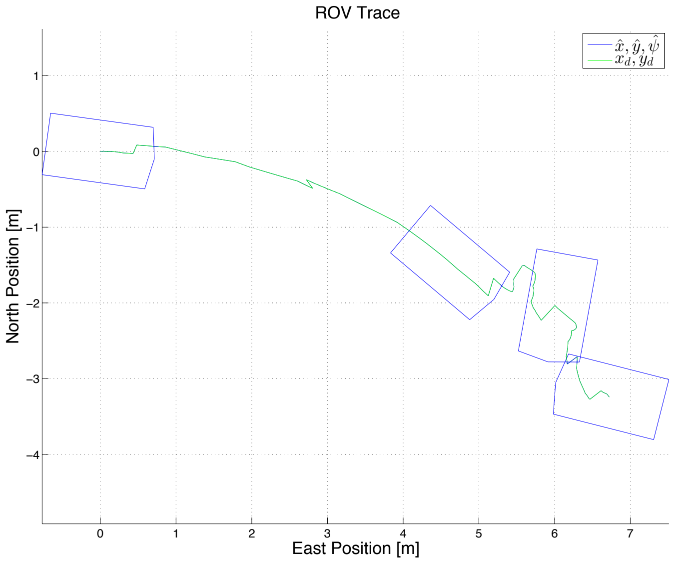


Figure 6.1: North-East plot of the ROV with direct thrust commands.

The fluctuations in the yaw commands from the joystick can be seen in Figure 6.3. More delicate movements of the joystick might provide a better result, and with further practices when knowing the behaviour might help improve the outcome. As a result of the unwanted movements, it takes almost 30 seconds before the ROV is fully stopped. The variations in movements are not ideal when moving close to an OOI.

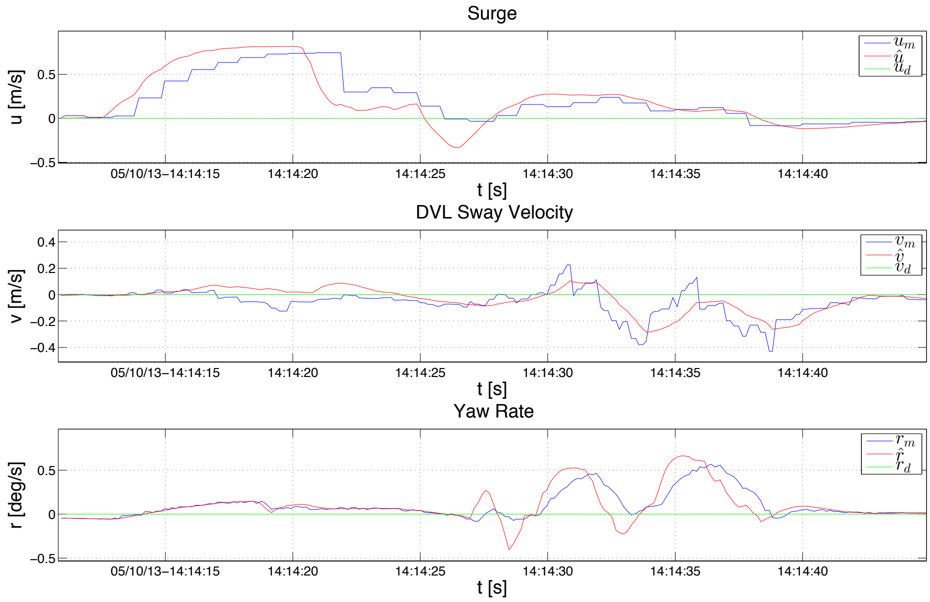


Figure 6.2: ROV horizontal velocities with direct thrust commands.

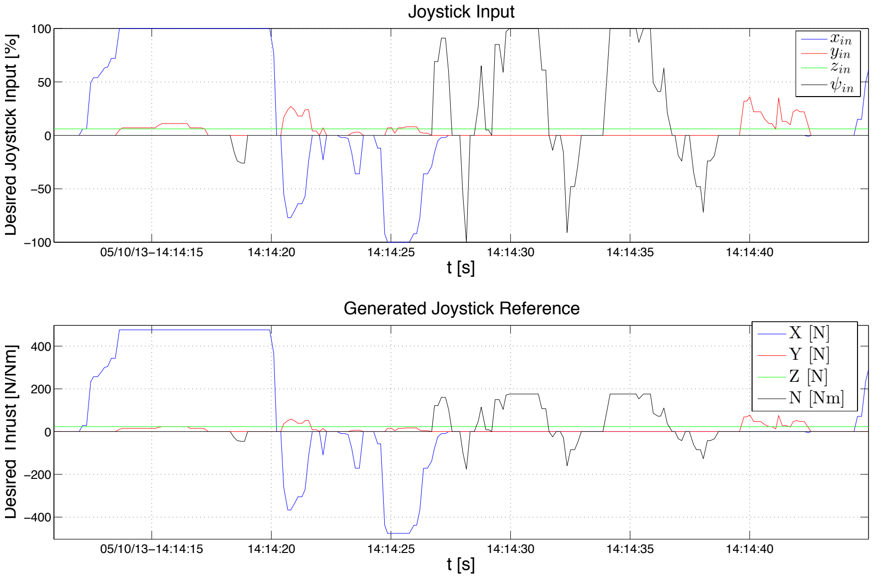


Figure 6.3: Joystick input and desired thrust with direct thrust commands.

Figure 6.4 shows the movement of the ROV commanded with the position method. In this case there is no unwanted heading movement during the full-stop. Similar to the simulations, there is an overshoot of the position that results in an unwanted movement backwards. It is moving 1 $m$ backwards, which is not ideal when the expectation is that the ROV will stop immediately.

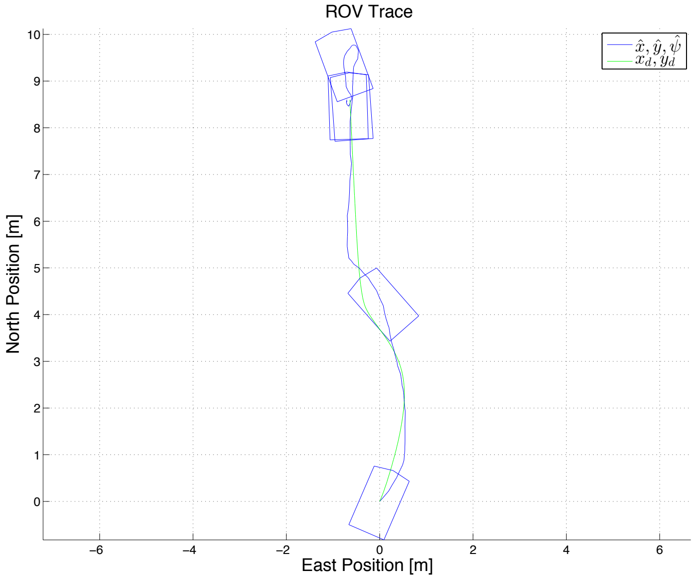


Figure 6.4: North-East plot of the ROV with position control method.

Figure 6.5 shows the ROV horizontal velocities. The desired velocity takes 3 seconds to reach zero, but due to the overshoot, it takes the ROV 22 seconds. The sway velocity and yaw rate are quite small, with the exception of some adjustments of the path in the start. Further tuning of the closed-loop controller might improve the performance. The idea behind the modified velocity reference model is to ensure a quick stop, but this test shows that there is still some work needed to make it better.

From Figure 6.6a we see that the joystick reference drops to zero, and the desired velocity in surge follows the exponential deceleration. The result is that the thrust changes sign, as seen in Figure 6.6b. There is a latency in the closed-loop control which results in a delay between the joystick input and the commanded thrust. This further reduces the pilots feeling of control, and is the reason for the difference in desired and estimated values during the sudden changes.

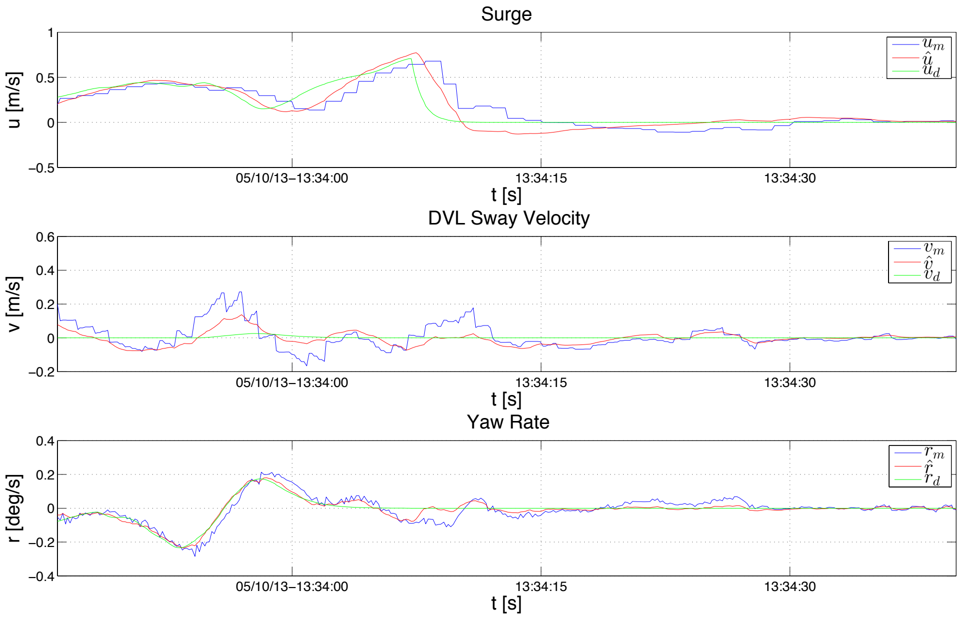
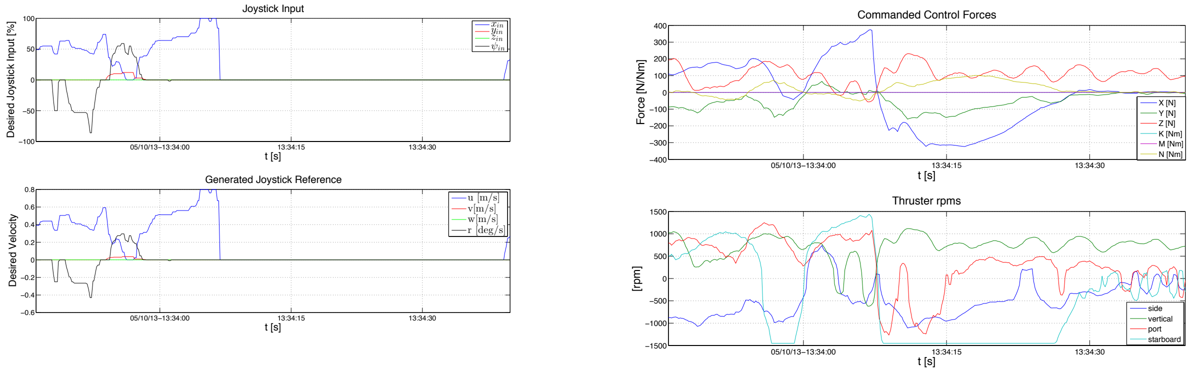


Figure 6.5: ROV horizontal velocities with position control method.



(a) Generated joystick input and desired velocities

(b) Generated desired thrust

Figure 6.6: Joystick input and desired thrust for position control method.

The used RPM on the thrusters are reaching max values, and the stop requires a lot from the thrusters. Using this form of stopping can result in a lot of wear and tear of the thrusters. This is not a problem for a test, but when used during a longer operation it increases the chances of down time due to repairs. Some more investigation of an approach with more economic thrust use should be further conducted.

## 6.3 Path Results

Figure 6.7 shows the movement of the ROV in the path when using thrust commands. The ROV moves in the planned pattern and the heading is much more centred towards the center of the half-circle then in the simulation results. ROV Minerva has a lot of extra equipment installed, and therefore the hydrodynamic loads of the simulation model are not accurate. There is more drag created by the ROV in this full-scale test, and that helps to slow down the movements faster and the performance increase compared to the simulation.

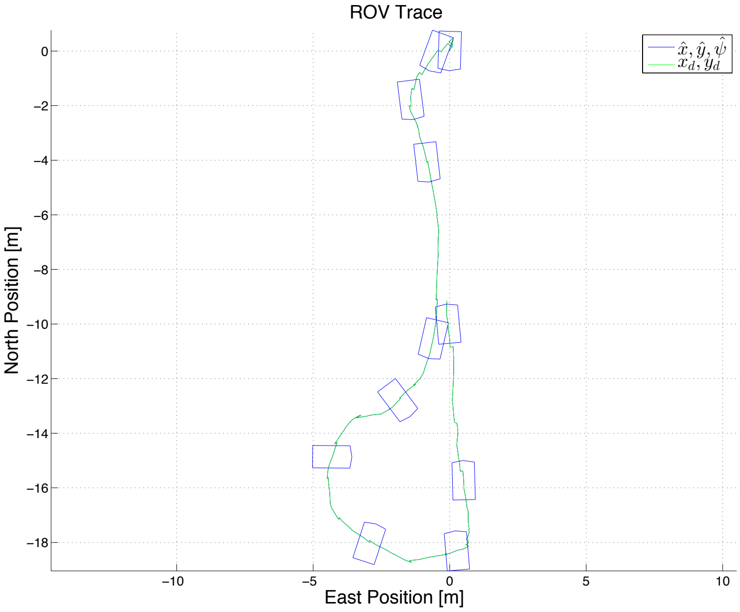


Figure 6.7: North-East plot of the ROV moving in a path with direct thrust commands.

In Figure 6.8 we can see the horizontal velocity profile for thrust commands. This is based on the joystick input and generated desired thrust seen in Figure 6.9. The velocities are varying due to the fluctuating joystick input, and the yaw rate has some drastic changes during the circular part. As shown earlier, it is hard to use thrust commands to come to a full-stop, and in the transition from surge to sway there is still a sideways movement.

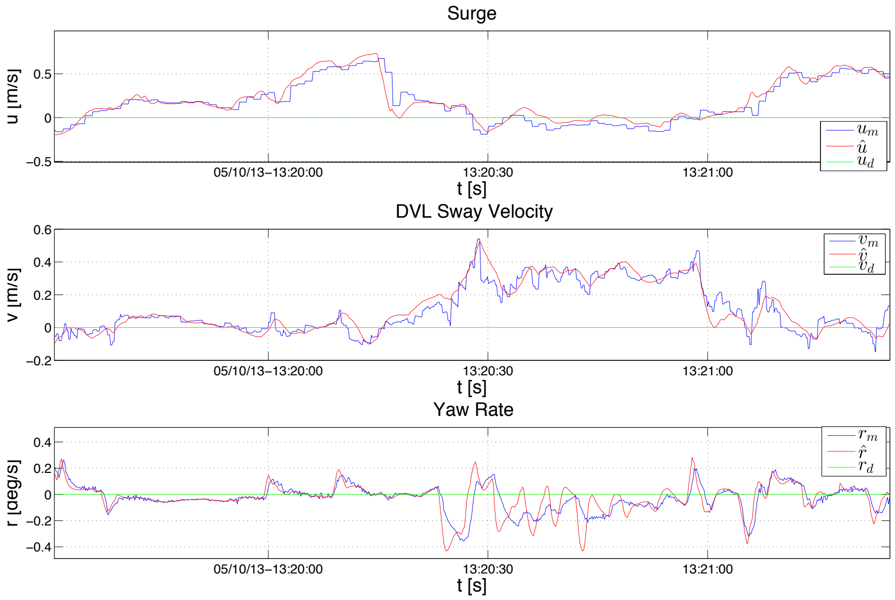


Figure 6.8: ROV horizontal velocities when moving in a path with direct thrust commands.

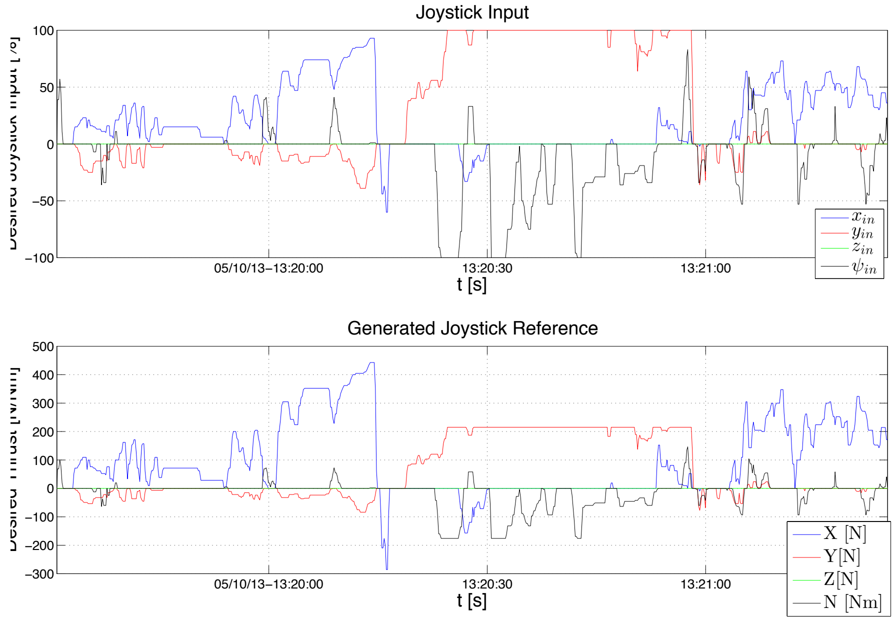


Figure 6.9: Joystick input and desired thrust with direct thrust commands

When using the position control method to move in a path we get the ROV movement as seen in Figure 6.10. When moving in a straight line the ROV is following the desired position, but the result in the circular pattern is more uneven. This comes from the big desired velocity in yaw as seen in Figure 6.11. When trying to initiate the change in heading, a big yaw rate is given as seen in Figure 6.12a. When compensating for this, the yaw rate increases too much. The delay between the desired yaw rate and the ROV yaw rate causes the pilot to be a bit behind, and the generated path becomes uneven. The solution is to make a full-stop, and the closed-loop controller stops the movement.

From the path we see that big and sudden joystick movements do not work well with the closed-loop controller, and the pilot needs to take this into consideration. The generated thrust forces can be seen in Figure 6.12b. The RPM levels for the thrusters are several times at the maximum level, and for long term use there should be a better handling of the economic aspect of the thrusters.

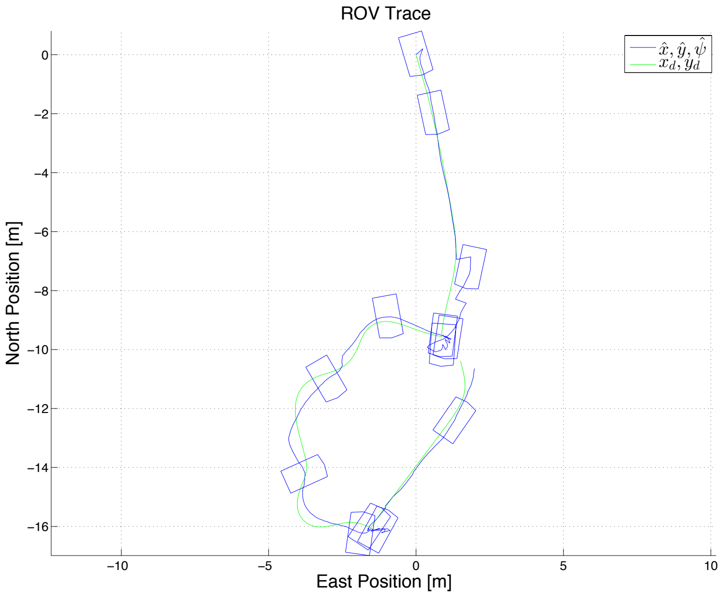


Figure 6.10: North-East plot of the ROV moving in a path with position control method.

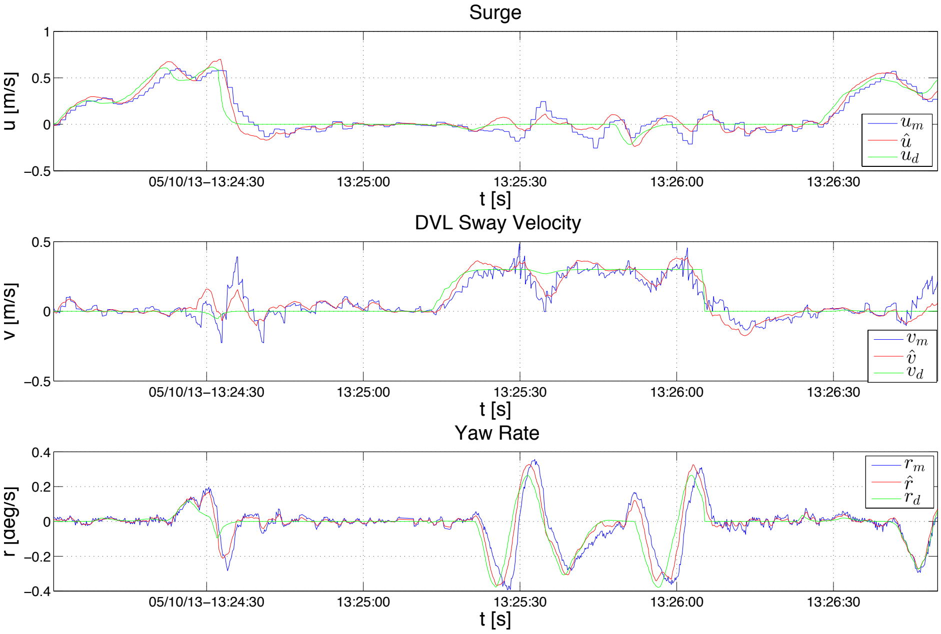
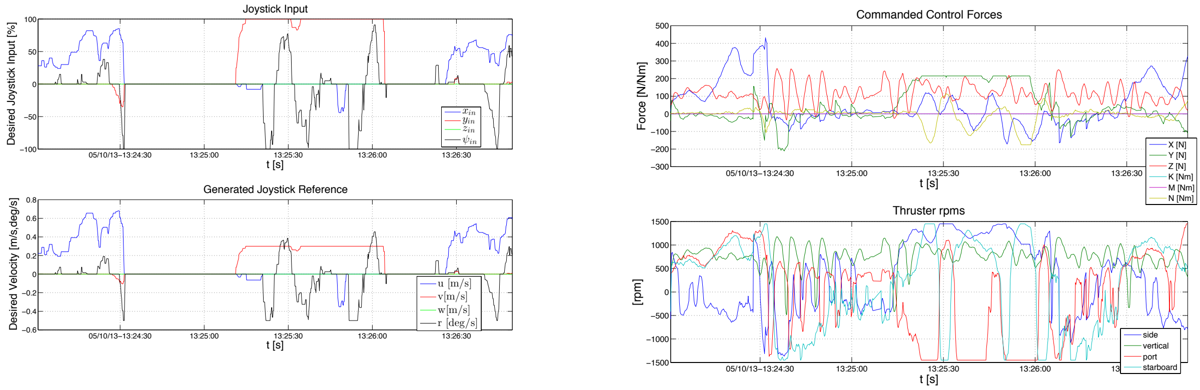


Figure 6.11: ROV horizontal velocities when moving in a path with position control method.



(a) Generated joystick input and desired velocities

(b) Generated desired thrust

Figure 6.12: Joystick input and desired thrust with position control method.

## 6.4 Discussion of the Full Scale Results

Full-stop and moving in a path have been tested full scale for thrust and position methods. Table 6.1 shows a summary of the most important parameters for the two methods. Through the full scale experiments some new aspects have been discovered that was not visible in the simulations. The most important being that the desired thrust calculated in the position mode is not economic and sustainable for the thrusters with long term use. Further the latency in the integrators for desired position causes a small delay that can be problematic for pilots that tries the position mode for the first time. Practice is required to use the full potential of the position method, and the path should ideally require few sharp turns.

Using thrust commands for a full-stop is not manageable for an unskilled pilot, and the position method is then a better option. This provides the opportunity to stop and get an overview of the area. The full scale test has shown that the position method, when used with smooth joystick references can be used for investigating an OOI, and that manual control in a path performs better then assumed in the simulations. Further graphs from the full scale experiment can be found in Appendix B.

| **Parameters** | **Thrust Commands** | **Position Mode** |
|---|---|---|
| Unwanted movements | Yaw (180°) | North (1 $m$) |
| Velocity Error | None to measure | Surge ($0,1\ m/s$) |
| Position Error | Non to measure | 1 $m$ |
| Overshoot | None to measure | Surge ($0,1\ m/s$)<br>Sway ($0,1\ m/s$) |
| Max RPM use | Port (1450)<br>Side (1400) | Port (1450)<br>Side (1450) |

Table 6.1: Comparison of path movement for the different control methods

# Chapter 7

# Concluding Remarks

This thesis has looked into different parameters and aspects that are important when developing an integrated environmental monitoring system. Some parts have been investigated with good results, while others still require more work. In this chapter the work will be evaluated and ideas for future work are presented.

## 7.1 Conclusion

The work in this thesis has focused on what approach to use when monitoring the underwater environment with the use of technology. An idea for a top level strategy is presented, as well as challenges related to the underwater environment. There are different platforms that can be used, and this thesis has focused on the ROV. Further the light and water properties were explored to investigate the causes and challenges with low visibility in underwater operations.

Joystick control has been implemented and tested in the body-frame with different scenarios. Both manual and joystick in a closed-loop control is thoroughly tested through the development of a joystick simulation system. To further enhance the pilot control, a modified velocity reference model was implemented. This showed promising results in the simulations, but with the need to be further calibrated. The simulations show that controlling the ROV with a velocity control is good for gathering images or video with the mobile platform.

Through full scale experiments the methods for manual and position control was further analysed. The position control shows promising results, but requires a different mindset from the pilot to fully utilize the potential. The full scale tests also revealed that the thrust use is very high, which is not good for long term use. The different joystick methods show good potential in operations where the ROV has a central role. The methods provide a new flexibility and reliability to the mobile platforms.

For coverage of an OOI, the suggested solution is to use the joystick in closed-loop control with the velocity method. This provides the least oscillation in velocity, and is most suited for taking images or video of the target. If the operation only requires a survey of an area and the velocity is not of importance, the position mode demonstrates the best qualities. The thrust method provides the chance of direct control, but also requires a trained pilot for good results. The conclusion cannot account for all operational situations, but needs to be adapted to each operation depending on the experience level of the pilot.

## 7.2 Recommendation for Further Work

When working on this thesis several aspects came to mind for improvement of existing work and new aspects that could be implemented. Most of this is connected to the joystick control to further increase the performance.

### 7.2.1 Future Work on the Strategy and UW Imaging

The strategy is meant to give the readers a starting point on what to consider when planning an IEM process. It is currently based on experience, and would benefit from being tested and evaluated in a live scenario. The strategy should also be worked on to incorporate scientific data to make it better and more user-friendly. The underwater imaging experiments were done with the help of SCUBA divers. The sensors and camera technology used can also be installed on an ROV. Further tests should be conducted to have data from different platforms for a better comparison.

### 7.2.2 Future Work on the Joystick Simulation System

The simulation system is now in a very basic stage. There is a full state feedback solution, and more elements can be incorporated to have a simulation closer to reality. There exists a full control system for ROV Minerva, but at the moment this includes other modes that are not needed to test the joystick functions. Development of the joystick simulation system can therefore benefit the further development of joystick control methods for ROVs. During the full scale experiments a bug in the system was discovered, as the desired depth changed when it should be constant. This should be further investigated to avoid similar problems on future tests. The system can also be more generalized to include options to choose different ROVs.

### 7.2.3 Future Work on Implementing Reference Frames

The focus on this thesis was originally for testing more reference frames. As the time was limited the NED frame was not tested, and cylinder coordinates did not get implemented. The cylinder frame can be very useful for circular motions, and should be developed as part of the joystick control system.

### 7.2.4 Further Work on the Pilot Experience Level

The work conducted revealed that it is difficult to predict the behaviour of the human-in-loop. This is hard to model, and highly depending on the experience level of the ROV pilot. Further testing of the joystick control methods should be done by different pilots. The tests can be used as a reference, and it might be possible to adapt the joystick controller to the different experience levels.

### 7.2.5 Future Work on the Closed-Loop Control

The closed-loop control used for position and velocity control can be further tuned and developed. The overshoot created in the deceleration phase is created by the velocity reference model and the closed-loop controller. These two parts should be further tuned to work better together, to avoid the backwards movement of the ROV when trying to achieve a full-stop.

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# Appendix A

# Parameters for ROV Minerva Used in Simulations

In the process plant model the parameters for the ROV is based on the work done by Kirkeby [2010].

The rigid body system inertia matrix is

$$M_{RB} = \begin{bmatrix} 460 & 0 & 0 & 0 & 55.2 & 0 \\ 0 & 460 & 0 & -55.2 & 0 & 0 \\ 0 & 0 & 460 & 0 & 0 & 0 \\ 0 & -55.2 & 0 & 111.9 & 0 & 0 \\ 55.2 & 0 & 0 & 0 & 110.6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 50.3 \end{bmatrix} \tag{A.1}$$

and the hydrodynamic system matrix is

$$M_A = \begin{bmatrix} 293 & 0 & 0 & 0 & 0 & 0 \\ 0 & 302 & 0 & 0 & 0 & 0 \\ 0 & 0 & 326 & 0 & 0 & 0 \\ 0 & 0 & 0 & 52 & 0 & 0 \\ 0 & 0 & 0 & 0 & 52 & 0 \\ 0 & 0 & 0 & 0 & 0 & 57 \end{bmatrix} \tag{A.2}$$

where the total mass is given as $M = M_{RB} + M_A$.

The nonlinear damping is

$$\mathbf{D}_{NL}(\nu) = diag\{292|u_r|, 584|v_r|, 635|w_r|, 84|p|, 148|q|, |r|\}$$

and the modifications to the linear damping is

$$
\begin{aligned}
D_{L,mod}(1) &= 0.8D_{NL}(1,1) \cdot e^{-2u_r^2} \cdot u_r, u_r > 0 \\
D_{L,mod}(1) &= 0.8D_{NL}(1,1) \cdot e^{-u_r^2} \cdot u_r, u_r < 0 \\
D_{L,mod}(2) &= 0.5D_{NL}(2,2) \cdot e^{-8v_r^2} \cdot v_r,
\end{aligned}
$$

The restoring forces and moments are

$$
g(\eta) = \begin{bmatrix} (W-B)s(\theta) \\ -(W-B)c(\theta)s(\phi) \\ -(W-B)c(\theta)c(\phi) \\ -(y_G W - y_B B)c(\theta)c(\phi) + (z_G W - z_B B)c(\theta)s(\phi) \\ -(z_G W - z_B B)s(\theta) + (x_G W - x_B B)c(\theta)c(\phi) \\ -(x_G W - x_B B)c(\theta)s(\phi) + (y_G W - y_B B)s(\theta) \end{bmatrix} \tag{A.3}
$$

where $s(\cdot) = sin(\cdot)$ and $c(\cdot) = cos(\cdot)$, with $W = mg$ and $B = W + 5N$, $r_G = [0, 0, 0.12]^T$m and $r_B = [0, 0, -0.15]^T$m. Further $m = 460$kg and $g$ is the acceleration of gravity.

The max thrust and max velocity of ROV Minerva is found based on experimental results. The maximum thrust is given by equation (A.4), and maximum velocity is given by equation (A.5).

$$
K_{js}^{\tau} = \text{diag}([476\ 215\ 389\ 176\ 176\ 176]) \tag{A.4}
$$

where $X$, $Y$ and $Z$ is in $[N]$ and $K$, $M$ and $N$ is in $[Nm]$.

$$
K_{js}^{\nu} = \text{diag}([1.03\ 0.5\ 0.5\ 0\ 0\ 60]) \tag{A.5}
$$

Where surge, sway and heave is given in $m/s$, while yaw is in $deg/s$.

# Appendix B

# Extra Full Scale Experiment Results

For the interested reader, this appendix provides the rest of the results from the full scale experiments conducted with ROV Minerva. This provides a further in-depth overview of the control methods tested.

## B.1 Full-Stop

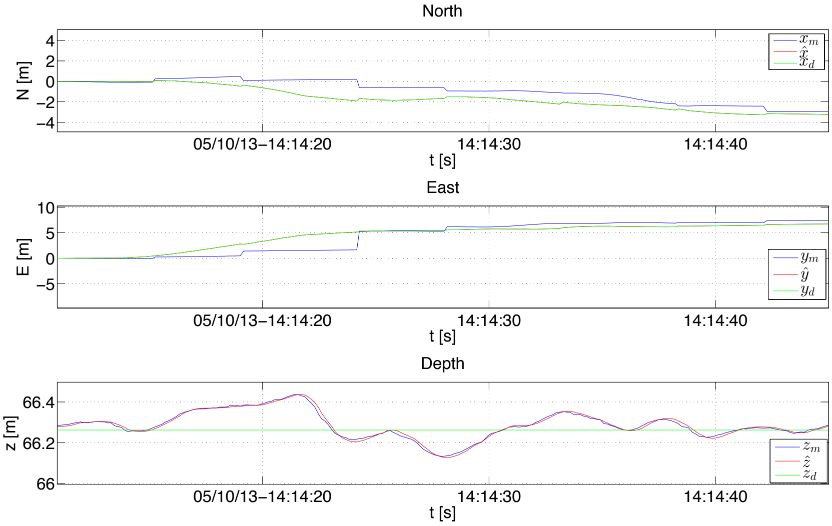

Figure B.1: North, East, Down plots of the ROV trying a full-stop with direct thrust commands.

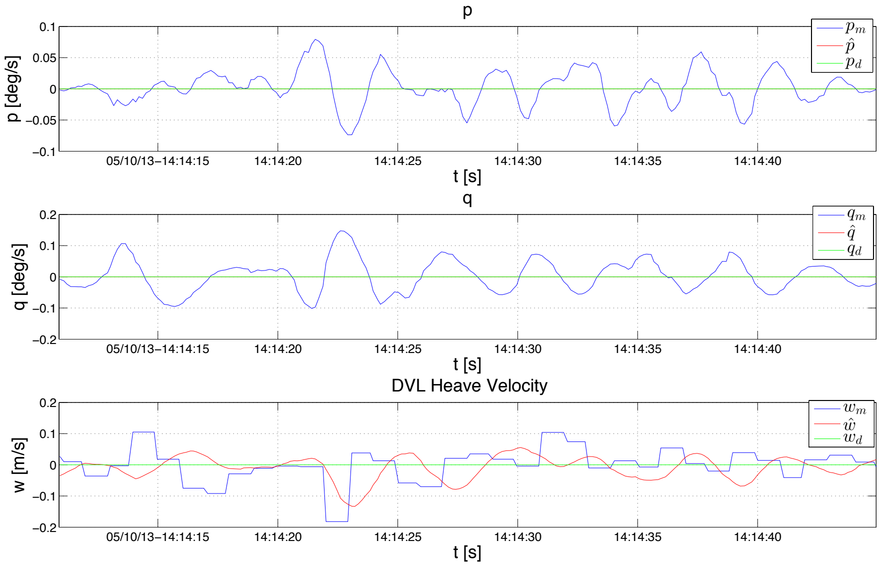

Figure B.2: ROV roll,pitch and heave velocities trying a full-stop with direct thrust commands.

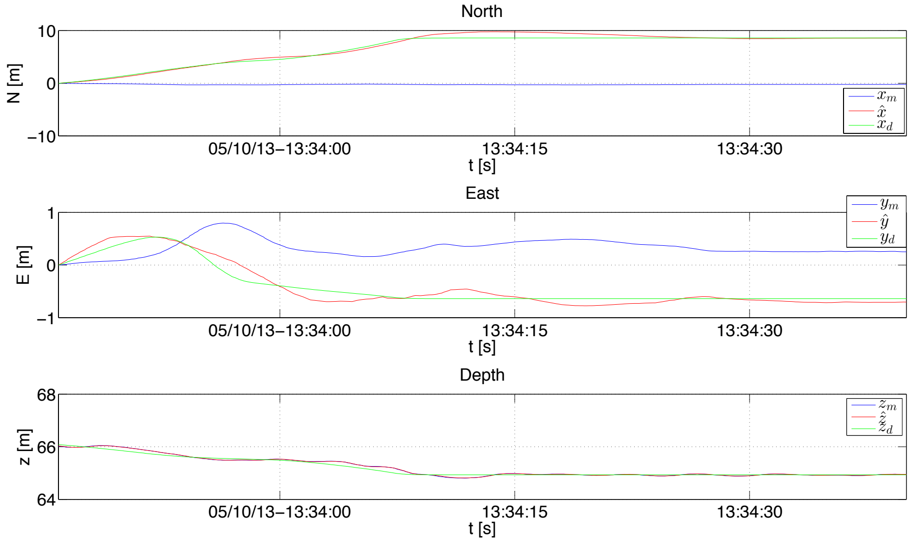

Figure B.3: North, East, Down plots of the ROV trying a full-stop with position control method.

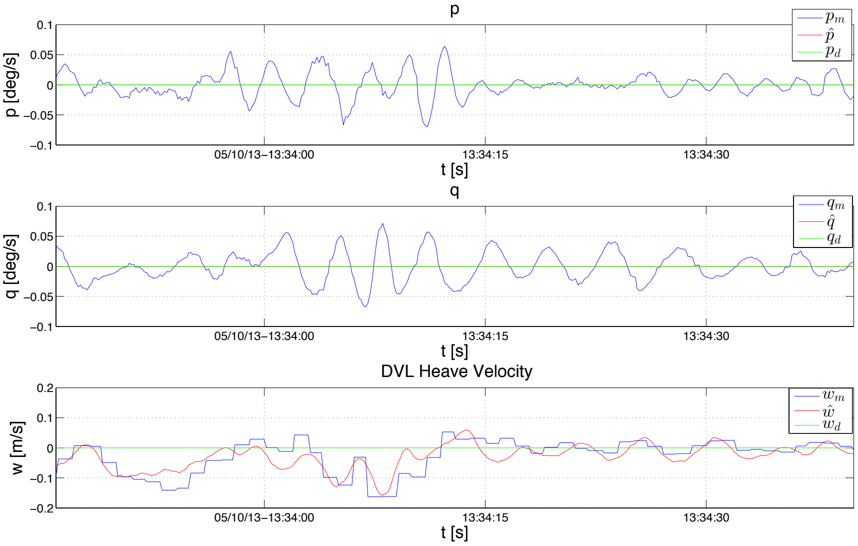

Figure B.4: ROV roll,pitch and heave velocities trying a full-stop with position control method.

## B.2 Path

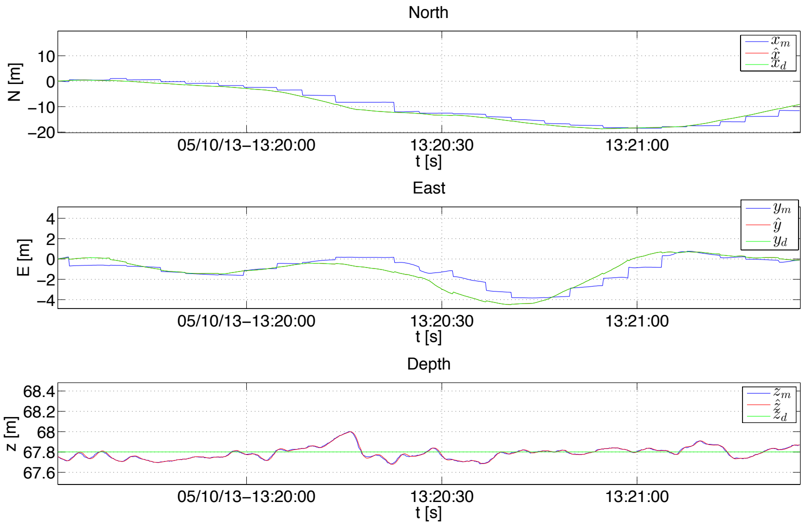

Figure B.5: North, East, Down plots of the ROV moving in a path with direct thrust commands.

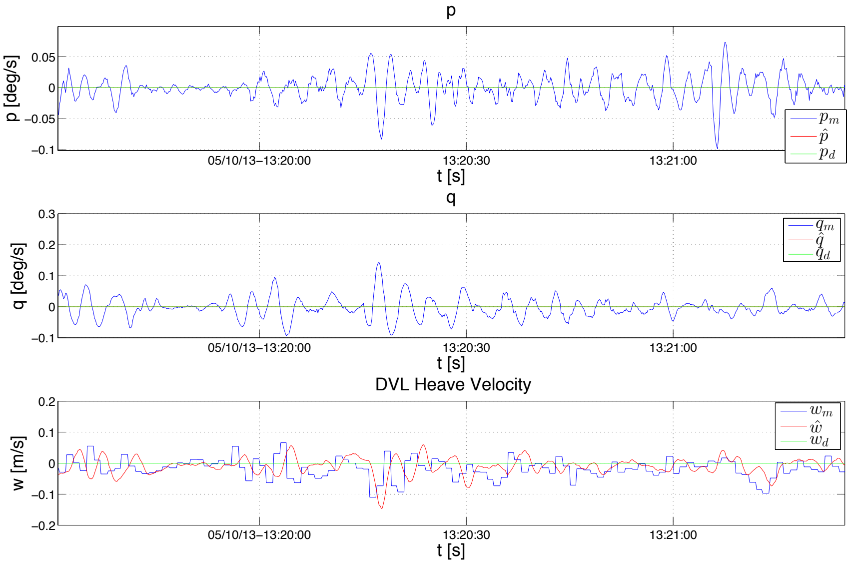

Figure B.6: ROV roll,pitch and heave velocities moving in a path with direct thrust commands.

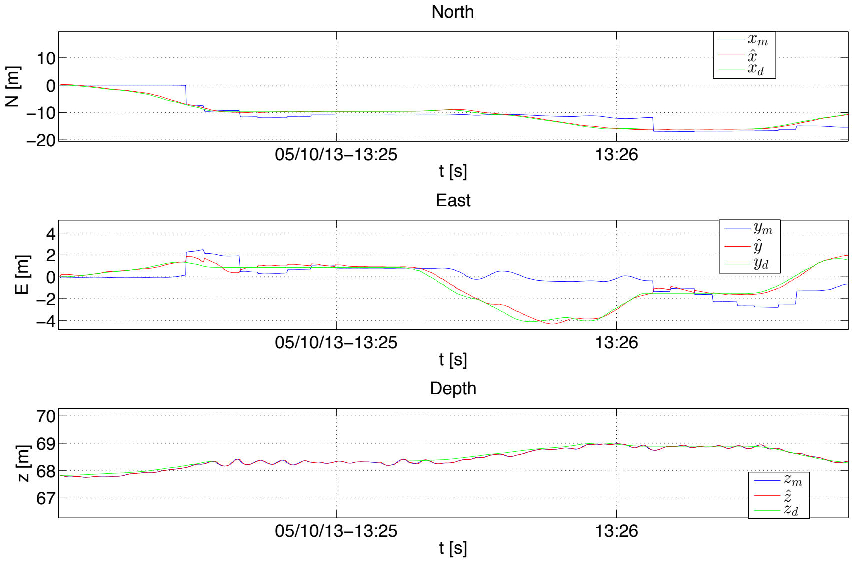

Figure B.7: North, East, Down plots of the ROV moving in a path with position control method.

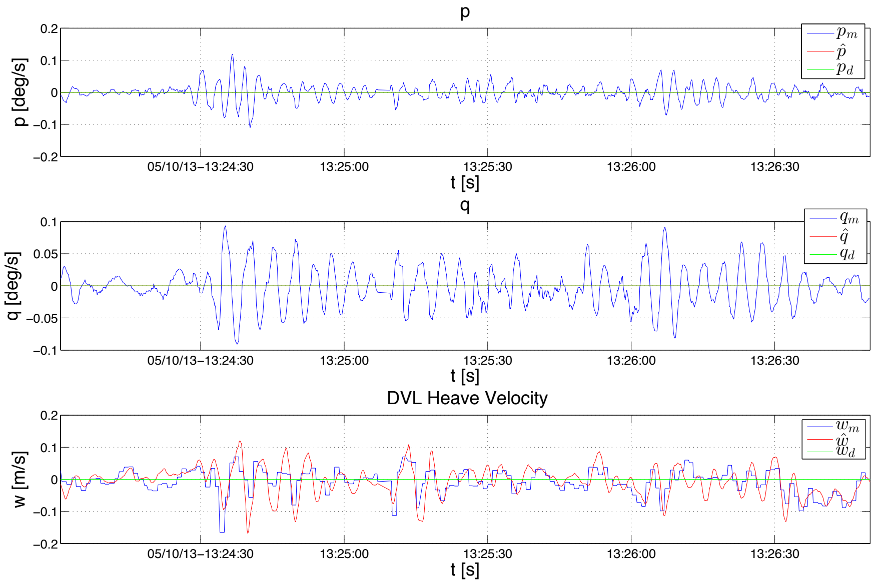

Figure B.8: ROV roll,pitch and heave velocities moving in a path with position control method.

# Appendix C

# Control Structure Overview

The mind-map in Figure C.1 shows the overview of the different control options. This is based on the control methods derived from the control system for ROV Minerva. The way to use it is by starting in the middle, and then choose a type of control. Continue out all the way trough the branches, and make a decision for each branch depending on what type of control that is interesting. In the end-branches there will be one type of configuration for each degree of freedom based on the options chosen along the way.

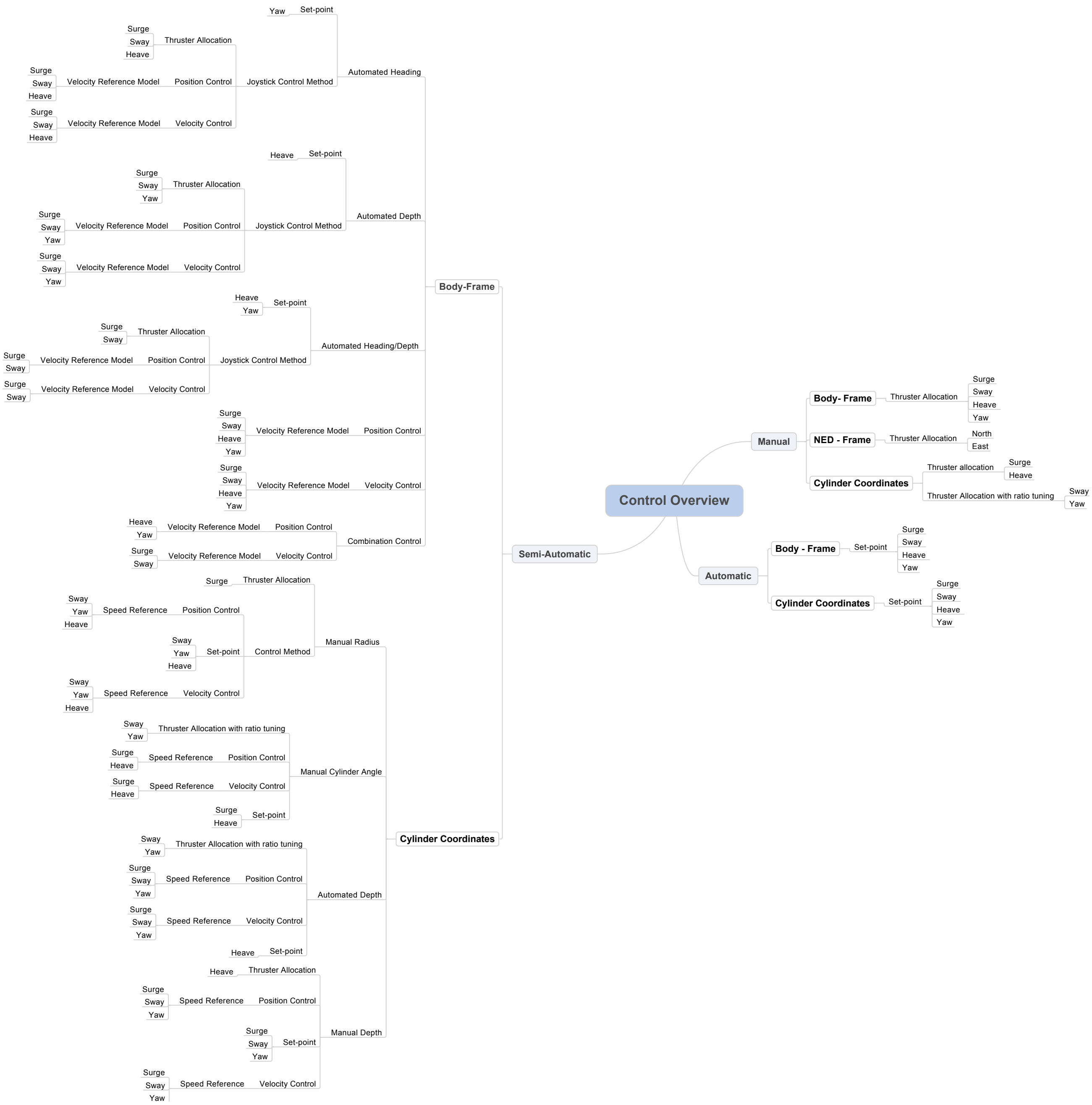

Figure C.1: Overview of the control structure.

# Appendix D

# Program Listing

The programs used in this thesis are included in a separate zip file.

The joystick simulation system requires LabView installed on the computer. It also requires a joystick to be connected to the computer. Due to some dependencies on other sub-VIs, the program is quite big. It will still work as long as it is run from the computer. To plot graphs of the output, a two Matlab scripts are included that is used solely for this purpose. These scripts require that a working version of Matlab is installed on the computer.

The programs included are

- In the folder 'ROV simulator test - with joystick' the following programs are included
    - Joystick Simulation System.vi that is used to run the joystick and ROV simulation.
    - log2mat_sim in the sub-folder 'Data simulations' to generate a .mat file of the logged data.
    - states_mat_plots in the sub-folder 'Data simulations' to plot the graphs of the logged data.
- Control_Structure_View.pdf is the more detailed overview of the control structure.
- Master_poster.pdf is the poster made for the Master Thesis Poster Exhibition at the Center for Marine Technology.