TTK4530

AUV Pipeline following and inspection

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Abstract

Abstract goes here. Remember to make it good.

Preface and Acknowledgments

This is the final report of the fall project at the Norwegian Univursity of Science and Technology (NTNU). This project are meant to preapere the undertaker for the master thesis, which is the last semester in the masters degree at NTNU. This is a project on how to write a project.

This project is also a pre-project to the masters thesis, an apetizer for the student to continue the project and really make it worth the time for the reader or a possible future employer.

For me this project has been a project to get to know all the problems associated with having an Autonomous Vehicle roaming the sea depths. We as humans, sentient beeings are perfectly capable of taking the numerous descisions where to go and what to do next. An Autonomous Vehicle need to be programmed, and for every single descision it needs to make, there must be some kind of rule. This makes the project huge and quickly gets out of hand for the designer working with it.

To create this kind of system much testing are needed, and a team of engineers to possibly cover all the aspects with a pipeline inspection mission. Kongsberg Maritime has been working on the *HUGIN 1000* for more than 15 years, and desingning an AUV for this kind of application are not done in half a semester at NTNU.

I like to thank Bjrn Gjelstad and ystein Engelhardsen at AUV R&D department, Kongsberg Maritime.

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Abbreviations & Notation

AUV	Autonomus Underwater Vehicle
CB	Center of Bouyancy
CG	Center of Gravity
DOF	Degree of Freedom
DVZ	Deformable Virtual Zones
ECEF	Earth-Centered Earth-Fixed
LOS	Line-of-Sight
MPC	Model Predictive Control
MPG	Model Predictive Guidance
NED	North-East-Down
PNG	Proportional Navigation Guidance
P_c	Point decomposed in the camera frame
P_i	Point represented in image coordinates
P_w	Point decomposed in world frame (NED frame)
ROV	Remotely Operated Vheicle
x_c	2D point decomposed in the camera frame
x_i	2D point in image coordinates

Introduction

Today there are over 3.5 million km of transmission pipelines in the world. 231 900 km pipelines are planned or under construction [DNV]. Pipelines currently in place need to continue operating, many of them far longer than they were initially intended. Great effort are taken to inspect and maintain the pipelines to keep them in satisfying order. The pipeline needs to be in working order to be operational. Potential leaks might cause irreversible environmental damages, and companies looses money when the flow through the pipeline are stopped.

There are two ways of inspecting pipelines; *internal* and *external* inspection. The internal inspection methods, includes stopping the flow in the pipeline, open it and insert a Pipeline Inspection Gauge (PIG) which travels inside the pipeline and uses various sensors to determine the state of the pipeline. The other method, *exterior* pipeline inspections are today mostly done using Remotely Operated Vehicles, ROVs. The ROVs are tethered unmanned underwater vehicles, and are the work horse of the offshore industry. They are versatile tools capable of accomplishing most missions associated with pipeline inspections and repair. However, they need well-equipped, expensive support vessels and a large crew to accompany the inspection mission which ofcourse are very costly for the pipeline owner. British Petroleum stats that the ROV are "overactuated" for the pipeline inspection case.[PK04]

An Autonomous Underwater Vehicle (AUV) is a suiting tool for pipeline inspection. An AUV is a untethered unmanned underwater vehicle. Opposed to the ROVs, which operation radius are limited by the tether, the operation radius of the AUV are limited by power consumption and battery life. An AUV comes in many forms, small or large. It may need minimal support crew which will minimise the cost for the pipeline owners. It can be made small enough to be launched from small ships, and even from shore to inspect pipelines going to the oil rafinery on land. This would be a greate advantage for the pipeline owners to cut costs, instead of hiring large support vessels and crew to support a pipeline inspection mission.

The speed of the inspections is also an important issue. A typical ROV has cruise speeds from $1-2$ knots ($0.5-1$ m/s), while an AUV has cruise speeds in the regime $2-6$ knots ($1-3$ m/s). This inclines that an AUV might cover larger area of pipelines than an ROV.

British Petroleum estimates that they can save up to 30 % by using AUVs for pipeline inspections instead of ROVs, which motivates the research in the area. The market for AUV doing pipeline inspections are present. The technology needed are present, and there are a number of companies developing AUVs for pipeline following. SeaByte and Subsea7 have conducted a successfull pipeline inspection mission using the *Geosub* AUV and claimed the world record in the longest uninterrupted pipeline inspection mission. The AUV inspected 22.2 km of pipeline at 4 knots without being interrupted. [Sea], [B08]

This report will look at the possibility to give the Kongsberg Maritime *HUGIN 1000* AUV the given abilities to track and follow a subsea pipeline. The AUV have hovering capabilities and are controllable in 5 degrees of freedom (DOF).The AUV are assumed stable in the *roll*. Although, the hovering abilities are present, this will not be used when designing the guidance system, becuase of the focus on energy efficiency.

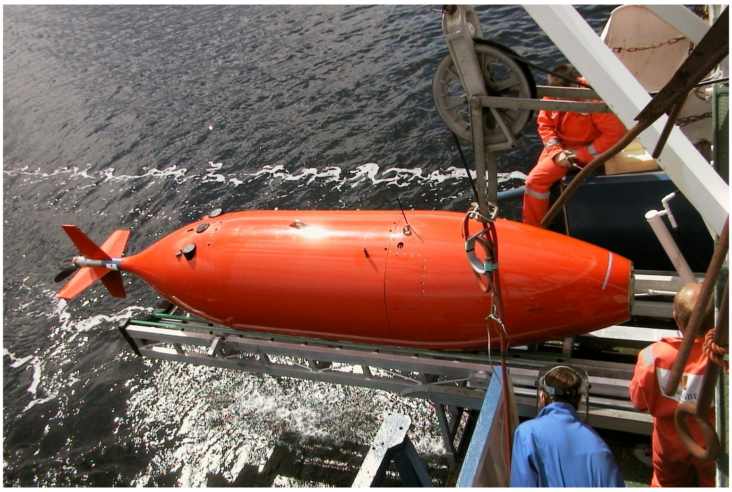


Figure 1: *HUGIN 3000* under launch. *HUGIN 1000* are somewhat smaller than *HUGIN 3000* but identical in shape

The pipeline detection equipment is a downward looking camera with sufficient lighting to operate at about 3-5 meters above the seabottom. Of course the visibility conditions will change according to depth and amount of particles in the water(naval snow). Probably this is an optimistic assumption, and at great depth the visibility will probably be less than 3 meters.

This report considers how to automate the pipeline inspections process. It will consider the possibility that the pipeline is buried under mud and not visible to the camera or buried on purpose to make it more robust towards environment forces and erosion, in both cases the important thing is to reacquire the pipeline at the end of the buried stretch. In that case some kind of an estimator have to be used to predict where the pipeline is headed.

A pipeline inspection mission can be divided into 4 parts:

1. Initialisation and initial descent
2. Search for and Acquire pipeline
3. Track and Inspect pipeline
4. Ascent to the surface and deliver the acquired data

The *Initial descent* and *final ascent* are self explanatory. But what happens if the pipeline are not at the initial position when, when the AUV arrives at that location? It is obvious that some kind of search need to be initiated.

The *Search and Acquire* part will need the vessel to move in some kind of search pattern if the pipeline is not located exactly where the initial position data states it to be. This search pattern should also be used if the pipeline is lost during tracking.

The *Track and Inspect* part needs a guidance system which is capable of keeping the vessel on top of the pipeline or in the vicinity, independent of the current in the area and other possible disturbances. This is necessary because the primary mission for the AUV is to provide video of the pipeline which can be used to determine the state and well-being of the pipeline.

This report is divided into four chapters;

1. Theory. Describes the necessary theory needed to understand the problem, and contains a summary of literature on the pipeline following subject.

2. Modeling, assumptions about the model and how it is modeled. A Kalman Filter and a flight-mode controller will be derived. The guidance system will be treated and desired beahviour will be treated.

3. Implementation and simulation of the proposed system. How the system are implemented and how it performes in certain situations will be treated in this chapter.

4. Discussion of the results given by the simulations, and various aspects about the proposed guidance system will be discussed. A review of how valid the results will also be given here.

5. Conclusion and future work will be treated in the last section. A summary of the results will be given and future work will be proposed.

Chapter 1

Theory

Pipeline inspection are a complex problem and include many engineering diciplines. This chapter introduces some of the basics about pipeline inspections when designing a guidance system capable of pipeline inspection. Basics on the mathematical model for *HUGIN 1000* will treated, together with some theory on how to model a camera view and how movement of points are described in the camera view.

1.1 Pipeline Inspection Fundamentals

To include the right sensors are an important aspect of making an AUV follow a pipeline. There are different sensors available which can be suited for this purpose. First the Multibeam Echosounder (MBE). Usually a Echosounder emits one beam of sound and measures the time of travel of the sound beam. A multibeam echosounder emits a fan of sound beams which can be used to map a larger area around the vessel.

A Side Scan Sonar are another practical sensor which could be useful. The Side Scan Sonar sends sound waves in the horizontal direction and provides good sensor data of the bottom around 200-300 meters in the horizontal direction. This sensor are usefull for initially finding the pipeline. A side scan sonar picture of a pipeline gives very distinct shadows and are easily detected.

1.2 Different Methods for Pipeline Following Discussed in Literature

A literature study was performed to see what other people have accomplished on the subject on AUV and pipeline following.

*************************************MORE**************************

[Hal91] describes briefly a prototype AUV equipped with a camera and sonar to carry out pipeline inspection missions. The AUV uses controllers for heading, speed and depth and visual guidance to follow the pipeline.

[NSAB03] proposes to use a two-stage guidance problem. When submerging and ascending to the surface, the AUV uses a LOS guidance law at full speed. When the pipeline is acquired the guidance law is switched to a visual guidance scheme, which allows for a precise guidance over the subsea cable or pipeline.

In [NRS04] a guidance system using Model Predictive Control (MPC) and PNG law was used to make a guidance system able to track cables and pipelines on the sea bed using Doppler Velocity Log and Electro- Magnetic sensors to find the cable/pipeline. The report utilises the pure pursuit scheme, similar to what predators do when they are hunting the pray. The cable/pipeline and AUV is formulated as moving points with mass. The engages in a tail chase with the pipeline “point”, but the AUV never catches up with it. This method is robust to model uncertainties and handles constraints of the vessel in a systematic way. The controller however shows problems when a current are introduced in the system. The AUV drifts of the pipeline, but catches up with the waypoints in the end. This is due to the fact that the guidance system are in a pursuit with the pipeline and the trajectory the AUV follows are not important. The guidance system only tries to catch up with the pipeline “point”.

In [For01] a visual guidance system for inspection of underwater structures is presented. The visual system uses an Extended Kalman Filter to smooth and predict where the structure i.e. pipeline will move in the next sample interval of for the image processing software. A three dimensional model of the scene is constructed which then allows the guidance system to calculate an input to the controllers.

[PJL05] proposes a reactive control approach to pipeline tracking together with a profiling sonar. Reactive control originated from the field of obstacle avoidance in autonomous land and air vehicles. It uses *Deformed Virtual Zones* (DVZ) which describes the interaction between the AUV and the pipeline. The controller tries to minimise the deformation of the DVZ and calculates a feasible control input. The DVZ in this case is a prism with a cylindrical cavity directly underneath the AUV. If the AUV moves away from the pipeline the DVZ will be deformed and the controller will try to counteract the motion. This is a computational inexpensive way of achieving a good pipeline following. This method shows promising results but has yet to be implemented and tested in real-life scenarios.

In [KU03] a fuel-optimal tracking controller is derived to minimise the fuel consumption of the AUV. It uses the fact that the least fuel consuming path is the shortest one. This paper derives a fuel optimal controller using the estimated fuel consumption as a minimisation index.

[PRB02] describes two techniques for detecting and tracking pipelines using Side Scan Sonar and Multi-Beam Echosounders. Prior knowledge about the pipeline are utilised for the recognition of the pipeline. A pipeline creates very distinct shadows in a side scan sonar image and are easy to separate from the sea bottom.

1.3 Reference systems

When treating motion of a system one will need some reference frame to calculate the motion relative too. There are a couple of different reference systems used. One is the ECEF-frame (Earth-Centred, Earth-Fixed), which has the centre of the earth as the origin of the frame. The frame rotates with the earth, but when the speed of the vessel is low, this frame can be considered inertial. [FB98]

Another common reference frame are the NED frame (North-East-Down).

It is defined as the tangential plane at the earth's surface moving with the vessel. It assumes that the Earth's rotation can be neglected, and this means that frame is not valid for inter-continental travel, because it is not strictly inertial. It is defined with the x-axis pointing towards the Earth's true north, the y-axis pointing towards the east, and the z-axis pointing downwards toward Earth's centre. The NED-frame is defined relative to the ECEF-frame by the means of two angles, *longitude* and *latitude*. This is the global reference system that will be used in this report. [Fos02]

The last reference system used is the Body-frame, which all forces, moments, linear velocities and angular velocities will be expressed in. This frame has it's centre in the Centre of Gravity (CG) of the vessel. The x-axis is defined in the longitudinal axis of the vessel, y-axis to the right, and the z-axis is directed downwards to complete the right hand-system. The body-frame values are transformed to the NED-frame by the means of a Rotation matrix.

1.4 Hydrodynamic Model

An Autonomous Underwater Vehicle is a complex, non-linear and coupled process. The model which is used in this report uses the 6 DOF model described in [Fos02].

$$\begin{aligned} \dot{\eta} &= \mathbf{J}(\eta)\nu \\ \mathbf{M}\dot{\nu} + \mathbf{C}(\nu)\nu + \mathbf{D}(\nu)\nu + \mathbf{G}(\eta) &= \tau \end{aligned} \tag{1.1}$$

where

$$\begin{aligned} \eta &= [N\ E\ D\ \phi\ \theta\ \psi]^T \\ \nu &= [u\ v\ w\ p\ q\ r]^T \\ \tau &\in \mathbb{R}^6 \end{aligned}$$

The Equation (1.1) describes the kinematics and kinetics for the model. It is in the mathematical sense just a Mass-damper-spring system. The Coriolis term, $\mathbf{C}(\nu)$, is a skew-symmetric matrix appering because the dynamics are formulated in a non-inertial frame.

The $\mathbf{D}(\nu)\nu$ matrix are the damping forces, including drag from the surrounding water. $\mathbf{G}(\eta)$ are the restoring forces acting on the AUV. The gravity and bouyancy forces are represented by six-dimentional vector.

The $\mathbf{J}(\eta)$ matrix is the rotation matrix of Euler coordinates which relates the velocity of the vessel to actual movement in the NED reference system.

1.5 Camera theory

The camera properties or parameters can be divided into two categories; the intrinsic parameters and extrinsic parameters. The intrinsic parameters are constant parameters and vary from camera to camera. It is the focus distance and image distortion of the pixels away from the centre of the camera. The extrinsic parameters relate the position of the point relative to camera coordinates. These parameters are of course dependant on the position of the camera and change with time. This imply that coordinates of a 2D point in the camera have to be transformed into a 3D point which can be used by the control system on board the AUV. Since we are going from less knowledge about a point to more knowledge about a point, some things are needed to be estimated or measured to gain the ability to solve the 2D to 3D problem exactly.[SHV06]

Suppose a point in the world reference system, denoted by, $P_w \in \mathbb{R}^3$. The same point represented in the camera frame, P_c are related to P_w by a rotation matrix, $\mathbf{R} \in SO(3)$. This gives the following equation:

$$P_w = \mathbf{R}P_c + O(t) \tag{1.2}$$

where $O(t)$ is the origin of the camera frame. This means that the point in the camera view is described by the equation

$$\begin{aligned} P_c &= \mathbf{R}^T(P_w - O(t)) \\ \mathbf{R}^T &= \mathbf{R}^{-1} \end{aligned} \tag{1.3}$$

A pinhole camera model are used to capture P_c to image coordinates, $P_i \in \mathbb{R}^2$. The principle behind a pinehole camera is that all lightbeams passes through a infinitesmall hole, or point, located in the origin of the camera frame.

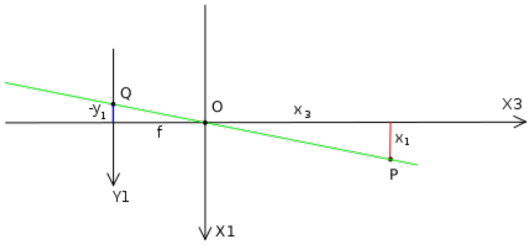


Figure 1.1: Pinhole Camera Model showing two dimentions

As seen from Figure 1.1 the image plane is located a distance f from the image plane. The point is projected through the hole an onto the image plane. The principal axis of the camere is located in the direction of the observed point. For simplicity the image plane are located in the front of the pinhole, this is just in theory and is not possible in real camera application. From this the perspective equations are derived. [SHV06]

$$P_i = \begin{bmatrix} \frac{f}{z_c} & 0 \\ 0 & \frac{f}{z_c} \end{bmatrix} \begin{bmatrix} x_c \\ y_c \end{bmatrix} \tag{1.4}$$

This are the perspective equations which gives the observed point in screen coordinates.

1.6 Kalman filter

Kalman filtering a powerful and versatile tool in estimation and sensor fusion. A Kalman filter is usually employed in navigation applications to fuse GPS and INS together. By this way one will have the speed and resolution of an INS system and the precision of the GPS system.

The Kalman Filter an optimal filter can be employed allmost in any application. It is optimal in the sense of providing the minimum-variance estimate of the predicted prosess. The Kalman filter is a linear filter, and can only guarantee optimality for linear systems. There is a nonlinear version of the Kalman filter, the Extended Kalman Filter, which uses the same assumptions as the linear version but uses the nonlinear model to predict the state forward while it used a linearised version of the measurement equation. When updating the Covariance matrix the system equations are linearised around the current estimate and updated according to certain update laws.

********************MER INFO************** This introduces some significant problems. First the filter might converge towards wrong values, because of a non-positive-definite covariance matrix. This is mostly due to poor linearisation of the state equations. [BH97]

1.7 Guidance

Most of the guidance algorithms originates from airborne missile systems. This have been well documented and proven to work in numerous cases. Common guidance schemes such as Line-of-sight (LOS) and Proportional Navigation Guidance (PNG) and various implementations of these are employed in numerous guidance systems.

Guidance are defined according to [Shn98]

Definition 1. *The process of guiding the path of an object towards a given point, which in general may be moving.*

It is also convenient to define two levels of guidance.

Definition 2. *The process of making an object converge geometrically to a given point or path is known as path following.*

Definition 3. *The process of making an object follow a gemoetric path with given dynamical constraints possibily dependant on position and time at the given path is known as trajectory tracking.*

The guidance systems discussed later will concern the first problem. The second problem will be disregarded and assumed that the dynamical constraints are constant and met. [BF05]

The guidance system need to adress the importance of a optimal paths. Optimal in the sense of energy consumption. A guidance system should be able to give feasible commands to the lower level control system which controls the actuators, and should be able to handle most situations with care. The guidance system should decide the best trajectory to be followed based on the target location and physical capabilities of the system.[NSAB03]

The Figure 1.2 shows the variables which are important for linear path following. The cross-track error, e are an important aspect here. It is the lateral position error decomposed in the desired path reference frame. Another variable worth noting is Δ which is the look-ahead distance. This is analogous to when you drive a car you look farther down the road to better maneuver the car. A great look-ahead distance yields less aggressive heading reference but slower convergence of the cross-track error. A lower look-ahead distance gives

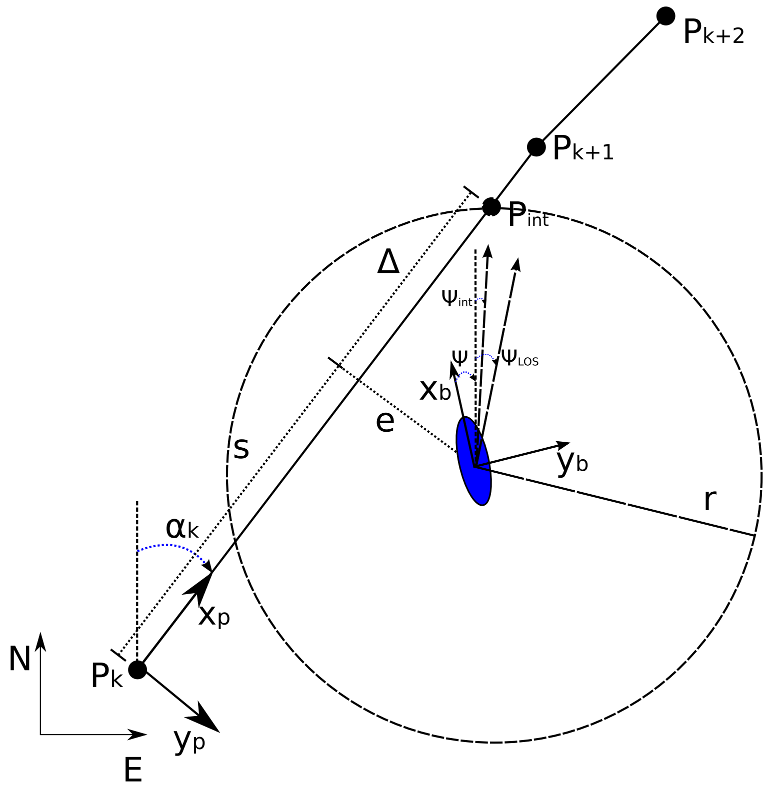


Figure 1.2: Variables associated with path following

an aggressive heading reference and fast convergence of the cross-track error. The s-variable are called the along-track distance from point P_k.

The choice of linear path following is because the simplicity asociated with the implementation, but this concept might easily be generalised to non-linear paths with the use of Serret-Frenet frame [EG02].

Line-of-Sight Guidance Law

Line-of-sight-guidance are the most common principle used. The LOS-algorithm computes the line-of-sight angle from the present location to the target location, and uses this angle as a reference heading.

The LOS-angle is fed directly into the heading controller as a reference. To make this law more tolerant to ocean currents and disturbances, a modified guidance law is presented. This uses the Side Slip angle, defined as:

$$\beta = \sin^{-1}\left(\frac{v}{\sqrt{u^2 + v^2 + w^2}}\right) \tag{1.5}$$

The Side Slip angle are the deviation of the velocity vector from the current heading of the vessel. The new heading reference is then taken as

$$\psi_d = \psi_{LOS} - \beta \tag{1.6}$$

Where ψ_{LOS} is the LOS-angle from the current position to the next waypoint.

Radius-based Guidance

Radius-based guidance uses the point where the radius around the current location intersects with the path, denoted on Figure 1.2 as P_{int}. This means assigning the desired heading as

$$\psi_d = \tan^{-1}(\frac{y_{int} - y}{x_{int} - y}) \tag{1.7}$$

where

$$(x_{int} - x)^2 + (y_{int} - y)^2 = r^2 \tag{1.8}$$

If r is chosen sufficiently large the equations above will have a solution, i.e $r > |e|$ otherwise there will exist no intersection point on the track line. [Bre08]

Lookahead-based Guidance

By using the direction of the line segment, path or pipeline, which finally are the desired heading that we want to achieve, ψ_d can be chosen as:

$$\psi_d = \alpha_k + \psi_r \tag{1.9}$$

where α_k is the direction of the path and

$$\psi_r = \tan^{-1}(\frac{-e}{\Delta}) \tag{1.10}$$

which can be seen as a correction term to make the dersired heading converge towards the path.

By choosing ψ_r in this way the heading is always directed towards the lookahead point at the path. It is then easily seen that the cross-track error will converge to zero. This method is easier and less computationally intensive than the previously stated Radius-based guidance. [Bre08]

Proportional Navigation

Proportional navigation guidance (PNG) are shown to give less interception time than LOS guidance, and therby reducing the distance traveled. [NSAB03]

The PNG-law can be stated as the following:

$$\eta_c = N' V_c \dot{\lambda} \tag{1.11}$$

where η_c is the acceleration command, N' is the navigation ratio, V_c is the closing velocity, and $\dot{\lambda}$ is the line of sight angular velocity. The navigation ratio is a tuning parameter which will give higher demanded acceleration and thereby reaching the target in less time.

Proportional Navigation Guidance can be shown to be optimal in case of a non-maneuvering target. When presented with maneuvering targets the scheme does not perform that well, but lots of solutions have been proposed to make these laws more effective when dealing with moving targets. In this case the targets will be non-moving waypoints and the maneuvering laws will not be discussed here.

Various Guidance Concepts

A unified path following controller are derived in [BF06]. The authors proposes a singel control structure which will work for the entire velocity regime. The controller is derived using backstepping. The concept are shown to be Uniform Global Exponentially Stable under some assumptions about the guidance signals. The controller will not work without properly generated references. The AUV considered here are fully actuated for low speeds but becomes underactuated for higher speeds. The controller guarantees that the AUV converges towards the desired path regardless of if it is underactuated or fully actuated.

In [BPP06] an optimal cross-track guidance scheme are proposed. It seeks to minimise the crosstrack-error, depth, pitch and yaw by using the pitch rate and yaw rate, this is called Model Predictive Guidance. Damping and can be added to reduce the commanded pitch and yaw rates which can cause overshoot. The guidance scheme are compared against a LOS guidance system and gives good results.

Chapter 2

Modelling

This chapter summarizes the problem and assumtions taken considering the pipeline following problem. A controller will be derived used for tracking and maneuvering of the AUV vehicle. A Kalman filter will be derived for the smothing and predictions of the pipeline and a guidance algorithm will be presented. The behaviour of the system will be treated in the last sections of this chapter, where the flow of the descision prosess will be presented.

2.1 Problem Outline

To solve the pipeline following problem it is important to have a clear formulation of the problem. This is a path following problem, since the pipeline can be represented as a continous path in space. The geometric convergence to the path is the primary objective. There can be dynamical constraints along the path, i.e velocity constraints but these are considered secondary to the goal of geometric convergence. When there are dynamic constraints the problem is a Trajectory Tracking Problem. If only geometric convergence are considered the problem is called a Path Following Problem. As stated in the definitions in Chapter 1.7

In this report the pipeline will be formulated as a two dimentional path. This because the pipeline are layed on the sea bottom, and are assumed to follow the bottom signature. Then the path following is reduced to a two dimentional problem. The *heave* state can be decoupled and in the controller design. The depth controller then needs to keep a constant height above the sea bottom. This ignores the posibility of free spanning pipelines.

In order to limit the problem and ease the implementation, the pipeline are assumed to be a stright or nearly strigth, piece-wise continous line segment. The pipeline can only change direction at defined places called junctions. The application of this guidance system are only for long, continous streches of piplines.

An AUV carrying out a pipeline inspection mission is in most cases a low speed assumtion is valid. The *HUGIN 1000* AUV are designed for speeds from 0-3 m/s. The inspection speed assumed in the rest of the report are around 1 m/s. This are realtively low speed, and the quadratic terms in the Coriolis/centripetal or Damping matices can be neglected.

As outlined in Figure 2.1 the building blocks of the pipeline following control

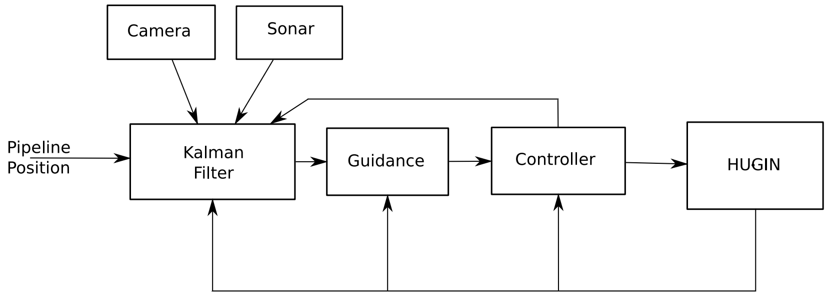


Figure 2.1: Block diagram the path following controller

system are the cruising controller, guidance system and the filter which fuses the known data about the pipeline and the measured pipeline data. To recreate the pipeline coordinates in three dimentions the distance to the sea bottom is measured by a sonar. The filter uses prior knowledge about the pipeline to-be-followd which can be inaccurate. The filter then uses this together with the altitude information and camera output to estimate the position of the pipeline. If the pipeline should be lost at any time the filter will try to predict where the pipeline are and serve as input to the guidance system.

The system should be able to handle burried sections of the pipeline. The camera will not be able to sense the pipeline during the burried strech and other sensors have to be included. A bottom penetrating sonar might be used for this purpose, or a magnetic pipe tracker. These sensors are able to sense the pipeline even if burried up to 3 meters. [B08] This sensors will give the AUV better chances to regain track after the burried strech than if it were to relay on just dead recogning from the predicted pipeline information alone.

2.2 Pipeline representation

The representation of the pipeline is important because it is used in the Kalman filter to predict where the pipeline is going. The pipeline is parametrized by $\varpi \in \mathbb{R}$ to get a continous and smooth pipeline.

In this report the pipeline are parameterized as:

$$P_w(\varpi) = \begin{bmatrix} \varpi \\ k_y \varpi \\ z(\eta) \end{bmatrix} \quad \varpi \in (0, \infty) \tag{2.1}$$

where k_y are constant and $z(\eta)$ is some function described by the sea bottom and are assumed known. This represents the straight line as the pipeline are assumed to be.

2.3 Kalman filter

The Kalman filters purpose is to smooth the camera output and predict forward where the pipeline will be in the future to supply a better heading reference for the guidance controller.

The position of the pipeline are given some uncertanty becuase the pipeline may have moved after it was layed or the navigation system of the AUV might be erronous. This gives:

$$P_w(\varpi) = \begin{bmatrix} \varpi \\ k_y\varpi \\ z(\eta) \end{bmatrix} + \mathbf{B}\delta \tag{2.2}$$

The function δ are a slowly varying disturbance which can be modeled as a *1st order Markov Process*, and $\mathbf{B}$ is some 2x3 matrix.

$$\dot{\delta} = -\mathbf{T}\delta + w \tag{2.3}$$

where $w \in \mathbb{R}^2$, are a zero mean unity variance white noise process. This describes the error in the position. The matrix $\mathbf{T}$ specifies how the error evolves. Because the error are slowly varying the eigenvalus of $\mathbf{T}$ should be chosen large. Time differentianting the position estimate with regard to time gives

$$\dot{P_w}(\varpi) = \begin{bmatrix} \dot{\varpi} \\ k_y\dot{\varpi} \\ \dot{z}(\eta) \end{bmatrix} + \dot{\delta} \tag{2.4}$$

By setting $\varpi = N(t)$, i.e the North position and completely disregarding the depth coordinate. gives the following

$$\dot{P}'_w = \begin{bmatrix} n \\ k_y n \end{bmatrix} + \dot{\delta} \tag{2.5}$$

Choseing the state vector and input as:

$$x = [P'^T_w \quad \delta^T]^T \quad \Rightarrow \quad \dot{x} = [\dot{P}'^T_w \quad \dot{\delta}^T]^T \quad u = n \tag{2.6}$$

This calls for the following state space representation

$$\dot{x} = \begin{bmatrix} 0 & -T \\ 0 & -T \end{bmatrix} x + \begin{bmatrix} 1 \\ k_y \\ 0 \\ 0 \end{bmatrix} u + \begin{bmatrix} \mathbf{0}_{2x2} \\ \mathbf{I}_{2x2} \end{bmatrix} w \tag{2.7}$$

The measurement model are more complex. In order to compare the measurement from the camera with the state space model, the perspective equations from Section 1.5 are needed. By using Equations (1.3) and (1.4), we can transform the point from World coordinates to image coordinates. We want $y = P_i$

$$y = P_i = \mathbf{H}P_c = \mathbf{H}\mathbf{R}^T(P_w - O(t))$$

$O(t)$ is the origin of the camera frame and is equal to the position vector $\eta' = [N(t), E(t)]^T$ of the AUV in the NED frame. By including the position vector in the input to the filter and using $P_w = \mathbf{C}x$, the measurement model are concelueded.

$$y = \mathbf{H}\mathbf{R}^T\mathbf{C}x - \mathbf{H}\mathbf{R}^T O(t) = \mathbf{C}'x + \mathbf{D}u \tag{2.8}$$

where $\mathbf{C}'$ and $\mathbf{D}$ are apropriate matrices for selecting the right states. $\mathbf{R}$ are the Rotation Matrix from World coordinates to Camera coordinates. This gives the following model for the Kalman filter

$$x = \mathbf{A}x + \mathbf{B}u + \mathbf{E}w \tag{2.9}$$

$$y = \mathbf{C}'x + \mathbf{D}u + v \tag{2.10}$$

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & -T_1 & 0 \\ 0 & 0 & 0 & -T_2 \\ 0 & 0 & -T_1 & 0 \\ 0 & 0 & 0 & -T_2 \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} 1 & 0 & 0 \\ k_y & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.11}$$

$$\mathbf{E} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \quad \mathbf{C}' = \begin{bmatrix} \frac{f}{z_c}\cos\psi & \frac{f}{z_c}\sin\psi & 0 & 0 \\ -\frac{f}{z_c}\sin\psi & \frac{f}{z_c}\cos\psi & 0 & 0 \end{bmatrix} \tag{2.12}$$

$$\mathbf{D} = \begin{bmatrix} 0 & -\frac{f}{z_c}\cos\psi & -\frac{f}{z_c}\sin\psi \\ 0 & \frac{f}{z_c}\sin\psi & -\frac{f}{z_c}\cos\psi \end{bmatrix} \tag{2.13}$$

w, v are a vectors of unity white noise and have covariance $E(ww^T) = \mathbf{Q}$ and $E(vv^T) = \mathbf{W}$. The filter should be run at the same frequency as the guidance system to provide output for the guidance system. The prediction will be updated whenever possible, which means when the pipeline are visible in the camera after the image processing are done.

Because of the relatively high frequency of the filter the parameters in the measurement model regarding heading and depth, i.e. ψ and z_c can be assumed constant during the sample period. This due to the slow dynamics of the AUV, compared to filter rate. This gives a linear model which can be guarantead to be optimal for the current case.

2.4 Controller Design

The model discussed in Section 1.4 is used to derive the controller equations for the AUV control system.

The control system which supply the lower-level control system with forces and moments references, is divided into 3 sub systems:

- Speed control
- Depth control
- Heading control

This is called the flightmode controller, which is used for normal pipeline tracking, descent and ascent. This type of controller where chosen because it will be more energy efficient than other more actuated controllers. The second reason is even if the AUV is almost fully actuated, i.e controllable in 5 DOF, the tunnel thrusters which have to be present for this degree of actuation are almost usless for higher velocities. This renders just control in 3 DOF, *surge, pitch* and *yaw*. This will probably give the most energy efficient pipeline following, because the control are based on the cheapest control modes available at the AUV.

The *HUGIN*-type AUV is a slender-body type AUV. This makes it possible to neglect some coupling effects between the states in the dynamic model. The *longitudinal* states (*surge, heave, pitch*) can be decoupled from the *lateral* states (*sway, roll, yaw*). This will be utilised in the next sections when deriving the control model and controller.

All coefficient next are defined in accordance with [SNA50].

Speed Controller

The speed controller is derived form the *surge*-subsystem, called *surge*-model [Fos02]. Under the slow speed assumption, the coriolis/centripetal-matrix is assumed zero, $\mathbf{C}(\nu)\nu \approx 0$

$$(m - X_{\dot{u}})\dot{u} - X_u u - X_{|u|u}|u|u = \tau_1 \tag{2.14}$$

Setting $\tau_1 = -K_p\tilde{u} - K_i \int \tilde{u}dt - K_d\dot{u}$ the error in the velocity reference will go to zeros. The velocity reference is assumed constant and the PID controller guarantees that the error will go to zero.

Depth Controller

To derive the depth controller in the crusing control system the *longitudinal*-subsystem is used as the control model [Fos02]. By assuming that the lateral states i.e v, p, r, ϕ, are small, the kinematics can be derived as follows:

$$\begin{bmatrix} \dot{d} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} w \\ q \end{bmatrix} + \begin{bmatrix} -\sin\theta \\ 0 \end{bmatrix} u \tag{2.15}$$

The dynamics of the system then becomes

$$\begin{aligned} &\begin{bmatrix} m - X_{\dot{u}} & X_{\dot{w}} & mz_g - X_{\dot{q}} \\ X_{\dot{w}} & m - Z_{\dot{w}} & mx_g - Z_{\dot{q}} \\ mz_g - X_{\dot{q}} & mx_g - Z_{\dot{q}} & I_y - M_{\dot{q}} \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \end{bmatrix} \\ &+ \begin{bmatrix} -X_u & -X_w & -X_q \\ -Z_u & -Z_w & -Z_q \\ -M_u & -M_w & -M_q \end{bmatrix} \begin{bmatrix} u \\ w \\ q \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -(m - X_{\dot{u}})u \\ 0 & (Z_{\dot{w}} - X_{\dot{u}})u & mx_g u \end{bmatrix} \begin{bmatrix} u \\ w \\ q \end{bmatrix} \\ &+ \begin{bmatrix} 0 \\ 0 \\ W z_b \sin\theta \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_3 \\ \tau_5 \end{bmatrix} \end{aligned} \tag{2.16}$$

Since the *surge*-speed are stabilized with the controller derived in the previous section, the surge equation can be removed from the system under the assumption $u = u_0$. Also by asuming that the *heave*-velocity and θ are small the control model becomes:

$$\begin{bmatrix} \dot{d} \\ \dot{\theta} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} 0 & -u_0 & 0 \\ 0 & 0 & 1 \\ 0 & -\frac{1}{\gamma}W & -\frac{1}{\gamma}M_w(m - Z_{\dot{w}}) - M_w Z_q \end{bmatrix} \begin{bmatrix} d \\ \theta \\ q \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{\gamma} \end{bmatrix} \tau_5 \tag{2.17}$$

where $\gamma = mI_y - mM_{\dot{q}} - I_y Z_{\dot{w}} + Z_{\dot{w}} M_{\dot{q}}$.

When closing the loop the following is proposed PID-like controller

$$\begin{aligned}\tau_5 &= -K_{dp}\tilde{d} + K_{dd}\theta + K_{dd2}q \\ \tilde{d} &= d - d_d \quad \dot{\tilde{d}} = -u_0\theta \quad \ddot{\tilde{d}} = -u_0 q\end{aligned} \tag{2.18}$$

A similiar controller are implemnted in [Jav94].

Heading Controller

Using the *lateral*-subsystem representation from [Fos02]. Under the assumtions that w, p, q, r, ϕ, and θ from the longitudinal subsystem are small, the kinematics are reduced to:

$$\dot{\phi} = p \tag{2.19}$$

$$\dot{\psi} = r \tag{2.20}$$

The low-speed assumtion is utilized, higher order velocity terms are neglected, and constant *surge*-velocity $u = u_0$ are— assumed. This gives the following system:

$$\begin{aligned}&\begin{bmatrix} m - Y_{\dot{v}} & -mz_g - Y_{\dot{p}} & mx_g - Y_{\dot{r}} \\ -mz_g - Y_{\dot{p}} & I_x - K_{\dot{p}} & I_{zx} - K_{\dot{r}} \\ mx_g - Y_{\dot{r}} & I_{zg} - K_{\dot{r}} & I_z - N_{\dot{r}} \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \end{bmatrix} \\ &+ \begin{bmatrix} -Y_v & -Y_p & -Y_r \\ -M_v & -M_p & -M_r \\ -N_v & -N_P & -N_r \end{bmatrix} \begin{bmatrix} v \\ p \\ r \end{bmatrix} + \begin{bmatrix} 0 & 0 & (m - X_{\dot{u}})u \\ 0 & 0 & 0 \\ (X_{\dot{u}} - Y_{\dot{v}})u & 0 & mx_g u \end{bmatrix} \begin{bmatrix} v \\ p \\ r \end{bmatrix} \\ &+ \begin{bmatrix} 0 \\ Wz_b \sin\phi \\ 0 \end{bmatrix} = \begin{bmatrix} \tau_2 \\ \tau_4 \\ \tau_6 \end{bmatrix}\end{aligned} \tag{2.21}$$

The *roll*-state can be removed from the equations because of the assumtions of small $\dot{p}, p$ and because of the vessel are considered stabel in roll because of the offset in the bouyancy point. The *sway*-velocity can assumebly be neglected, the sway subsystem can be removed as well. This can be seen from the simulations later in the report.

The following control model are used to derive the heading controller. The model is really the 1st order Nomoto model, and have become famous for it simplicity yet prove to give good results.

$$\begin{bmatrix} \dot{\psi} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & \frac{N_r - mx_g u_0}{I_z - N_{\dot{r}}} \end{bmatrix} \begin{bmatrix} \psi \\ r \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{I_z - N_{\dot{r}}} \end{bmatrix} \tau_6 \tag{2.22}$$

The following heading controller are proposed:

$$\tau_6 = T\dot{r}_d + r_d - K_{hp}\tilde{\psi} - K_{hi}\int \tilde{\psi} dt - K_{hd}\dot{\tilde{\psi}} \tag{2.23}$$

The terms $T\dot{r}_d + r_d$ are reference feed forward terms which will guarantee perfect tracking during course-changing maneuvers according to. This requiers a smooth reference signal and care must be taken to calculate it. [Fos02]

2.5 Summary of Assumtions

A summary of the assumtions are given here:

1. The pipeline is layed on the sea bottom, which gives the pipeline the same height signature as the sea bottom. The guidance problem is then reduced to a two-dimentional problem. No free-spanning pipelines are present.
2. Pitch- and roll angles, are assumed small together with the corresponding pitch- and roll rates. In the vicinity of $\pm 10°$ and ± 0.05rad/s
3. *sway* and *heave* velocities are small compared to *surge* velocity and any cross-coupling terms may be neglected.
4. The full state are assumed perfectly known, i.e. velocity and acceleration of the AUV.
5. The exact position of the are known.

2.6 Guidance system

An autonomous system is by definition a system that will have minimal interaction from humans, it is supposed to do things on its own. This is the guidance systems task. Figure 2.2 shows a proposal of a guidance and descision system for the *HUGIN 1000* vehicle.

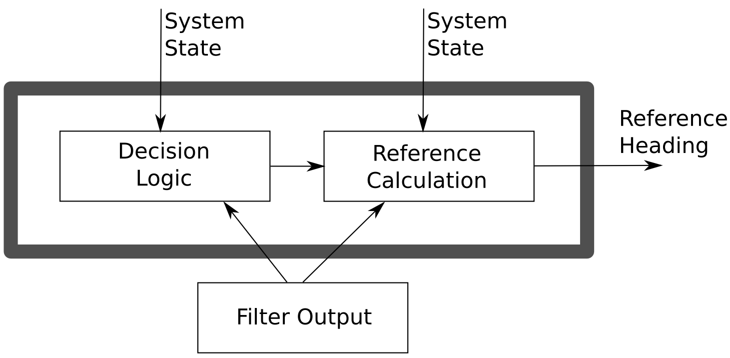


Figure 2.2: Guidance System Block

The AUV guidance system are assumed to have three modes, *searching*, *tracking* and *initialize/finalize*. The *initialize/finalize*-mode are the beginning and end of a mission and will not be considered in this report.

The *searching*-mode are when the AUV are looking for the pipeline. When the pipeline are layed on the sea floor, the position may be more or less inexact. Both because of sometimes the great distance from the sea level and to the sea bottom, and sometimes because the pipeline have "sagged", i.e moved away from the initial position because of movement in the sea bottom caused by sea currents and other environmental forces.

Figure 2.3 shows the searching procedure. It shows the descisions that the descion block need to handle. The system distinguishes between the cases if the

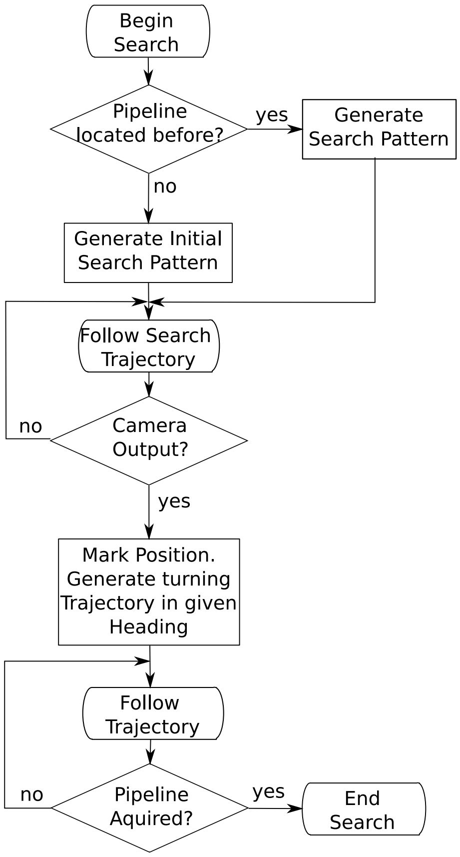


Figure 2.3: Flow diagram of the search procedure in the *searching*-mode

pipeline have been located before, or not. If the pipeline have not been located before, the system generates a initial search pattern, which should be designed to cover larger area. If on the other hand the pipeline have been located before, and tracking have been initialised, another pattern should be generated. The system then follows this search pattern until it gets output from the camera, or other possible sensors. Then the position are marked and a turning trajcetory are generated. When the pipeline then is reaqcuired the guidance system goes to the tracking mode.

When in the *tracking*-mode the AUV tries to follow the pipeline as closly as possible, and keep the pipeline inside the field of view as best as possible.

Reference Calculation

A look-ahead based guidance algorithm is chosen for it's simplicity and robustness. All together a pipeline are made up of mostly linear segments or at least almost linear segment. One can then assume that the direction of the pipeline can be known exact. No sudden turns are assumed and pipeline junctions are assumed to be non excisitng. This gives the following equations, some are

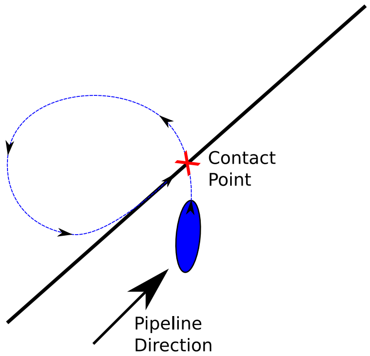


Figure 2.4: A turning trajectory for one possible contract

treated in Chapter 1.7.

$$\psi_d = \alpha_k + \psi_r \tag{2.24}$$

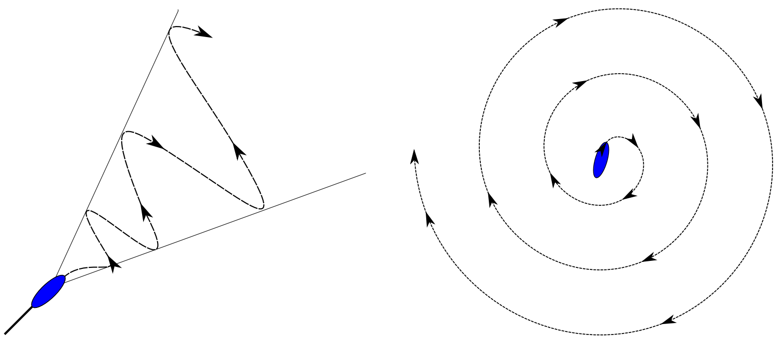
$$\psi_r = \tan^{-1}\left(\frac{-e}{\Delta}\right) \tag{2.25}$$

$$e = -(n(t) - p_x)\sin\alpha_k + (e(t) - p_y)\cos\alpha_k \tag{2.26}$$

In the presence of ocean current it will cause the heading to "lean" towards the current if the look-ahead distance is not chosen too far away. There will be some kind of equalibirium between the current and the AUV heading. This will will work well under the assumption that the current are constant.

Search Patterns

It is obvious that some kind of search pattern must be implemented for this kind of application. This might be customized for every mission or it might be selected from a library of suiting search patterns. This section will look at some search patterns which might be suiting for the pipeline search application.



(a) Divergent Zig-Zag pattern for lost pipeline during tracking

(b) Outwards spiral pattern for inital pipeline search

Figure 2.5: Differnet search pattern

The first case is when the pipeline are not in its predetermined position or the position sensors gives out erronous readings, some kind of search need to be initiated to find the pipeline. This could be something like the depicted case in Figure 2.5(b). Spiral pattern going outwards to try to find the pipeline in the visinity of the AUV position. This should be aided with other sensors for example with a Side Scan Sonar which provides good sensor data in the horizontal directions around the AUV.

The other case is when the pipeline are lost during tracking. Since the general direction of the pipeline are assumed known, the other pattern are a divergent zig-zag pattern around the assumed pipeline trajectory, from the last known position.

The search pattern can be created using polar coordinates from the current position of the AUV. The parameters, area in the initial search pattern or the spread angle in the divergent zig-zag should be customised for each mission.

2.7 Overall System

The system flow are depicted in Figure 2.6. This is how the overall system behaves during a pipeline inspection mission. The system will start by moving

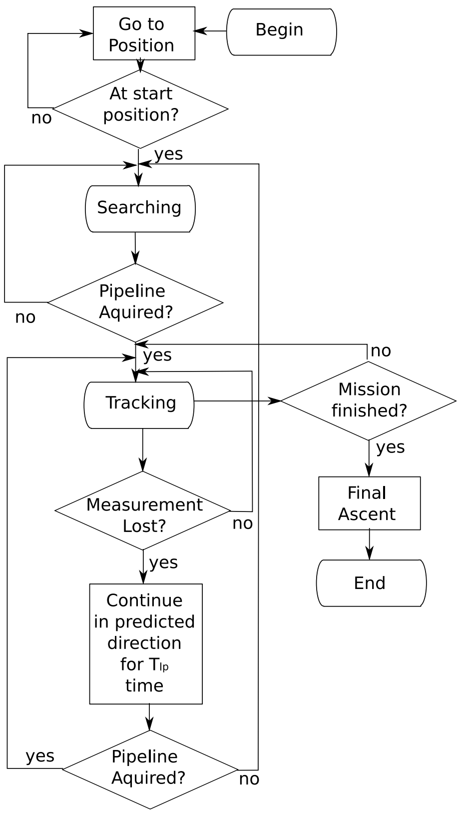


Figure 2.6: Flow diagram of pipeline inspection mission

to the point where the inspection should start. Then the searching procedure will be initiated if the AUV does not make contact with the pipeline imediatly. It will search for the pipeline until it has located it and then continue tracking until the the goal are met or the onboard energy storage becomes depleted.

There are a number of design parameters needed to be set. These parameters might be constant or changing between missions. They are summarised in Table 2.1 These parameters should be chosen in accorance with what kind of

Design Parameter	Description
T_{lp}	The Dead recogining time. Time before pipeline are considered lost.
Δ	The lookahead distance, descinding the convergence of the heading to the path
α_k	The general pipeline direction, need to be specified
P_w	The predicted path of the pipeline in world coordinates or a prametrization of it
$\mathbf{T}$	The values of this matrix must be chosen in accordance with the uncertainty of the predicted pipeline path. Usually chosen large
$\mathbf{Q}$ & $\mathbf{W}$	The covariance matrices of how much you want to trust the predicted values of the pipeline and the uncertainty of the measured ones.

Table 2.1: Summary of design parameters in the system

envirionmanetal forces there are in the area. Also the search patterns should be customised for every mission. Set how much area they need to cover, and vary the spreading angle of the divergent zig-zag pattern in accordance with how certain the direction of the pipeline are.

Chapter 3

Simulations and Results

To test the performance of the proposed guidance system, it is implemented in matlab/simulink. A number of scenarios are used to test how it performes in various conditions.

3.1 Matlab

The mathematical model of the *HUGIN 1000* AUV are implemented in simulink using the *GNC* toolbox available from *www.marinecontrol.org* with slight modifications to the 6DOF model.

The Camera output simulator were programmed in matlab. It inputs the position of the AUV and transforms it to body coordinates to calculate the field of view of the camera. The camera are based on the pinhole camera model with unity focus distance, and a view angle of about 45 degrees. The program then calculates the field of view of the camera and checks if there are any part of the pipeline inside the field of view. The output of the camera are three points taken out at the top, the middle and the bottom of the field of view. See Algorithm 1

Algorithm 1: Camera Simulatior($\eta(t)$, $z_b(t)$, f)

FieldOfView $= f(\eta(t), z_b(t), f)$
if Pipeline inside FieldOfView **then**
  PipelineSegment inside FieldOfView to image cooridnates
end if
return PipelineSegment in image coordinates

A sonar which determines the altitude are implemented using a look-up table with a predefined bottom profile.

The descision logic is implemented as a state machine with three states, and gives out the desired heading dependent on what state the system is in. This implementation is in correspondance with Figure 2.6.

The filter was created using a m-file and global variables for the filter parameters. The filter parameters are as follows:

$$P_0 = \begin{bmatrix} 10 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 \\ 0 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0.1 \end{bmatrix} \quad W = 0.1\mathbf{I}_{2x2} \quad Q = 10\mathbf{I}_{2x2}$$

The **T** matrix are chosen to be diagonal with 1000 at both elements.

The final simulink diagram are shown in figure 3.1. The structure of the

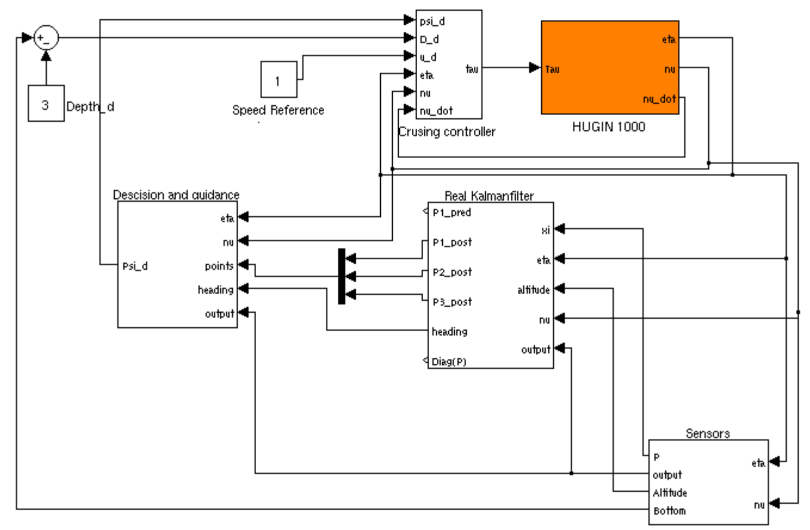


Figure 3.1: The Simulink Diagram of the implemented Guidance System

model are strictly modular and the blocks shown in the simulink diagram have the same function as in Figure 2.1. This allows to update and improve the different blocks individually, without designing a new system.

3.2 Simulation Scenarios

To test the performance of the guidance system some scenarios are proposed. In all the scenarios the pipeline are located at the sea bottom around 10 meters bellow the surface.The depth is arbitarily chosen and the value does change the scenarios except that the submerging time is longer. The AUV will start at the surface and submerge towards the starting point of the pipeline or the mission.

1st Scenario. The pipeline are at the exact location acording to predefined data. Environmental disturbances such as currents are turned off. The pipelien are continiously visible for the camera the whole inspection distance. Reference simulation.

2nd Scenario. Exact as over but with environmental forces turned on.

3rd Scenario. The pipeline are at the exact location where it initially was layed. A section is burried, and not visible for the camera. Environmental forces are turned on.

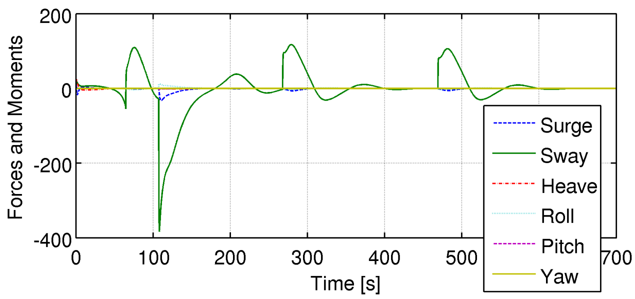
4^{th} **Scenario.** The á priori information about the pipeline are offset about 50 meteres to test the ability of the guidance system to search for the pipeline.

3.3 Results

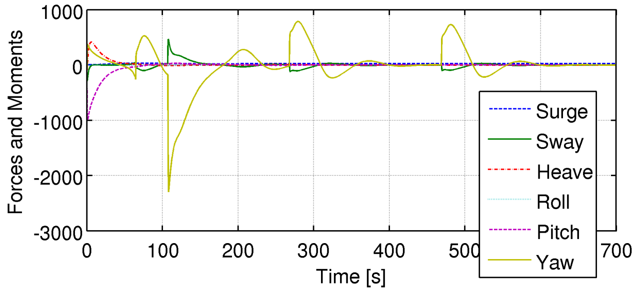
The matlab/simulink implementation were simulated with the given setup. A simulation were done to check if the low speed assumptions were valid. After this the simulation of the scenarios were done and produced the followin results.

Test of the low-speed assumtion

In figures 3.2(a) and 3.2(b) the forces and moments created by the Coriolis/centripetal and damping matrices are recorded. In Figure 3.2(a) the sway degree of freedom are dominant, and peaking about -400N during the turning maneuvers of the AUV. The forces and moments created by the coriolis terms are partially counteracted by the damping terms, that also have greated magnitude than the coriolis terms. This suggests that the coriolis/centripetal



(a) Coriolis Forces



(b) Dampering Forces

Figure 3.2: The Forces associated with the AUV maneuvering

forces can be neglected and compensated for as model errors in the controller using integral terms.

1st Scenario

This is a reference test to see how the guidance system performs on the ideal case. To show the sensitivity to the envirionmental disturbances, introduced in later scenraios.

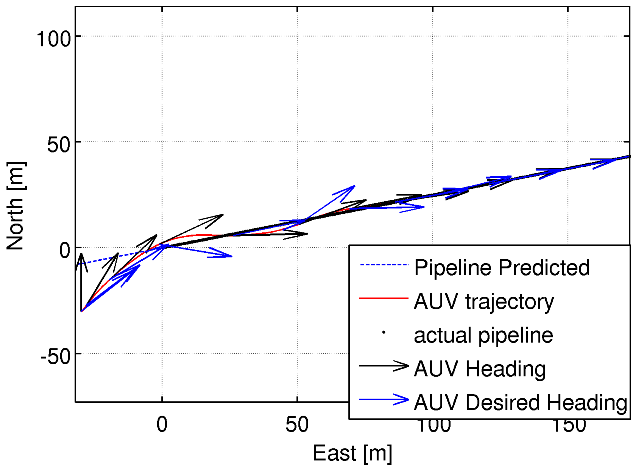


Figure 3.3: North East path of AUV without Current

It can be seen from both Fiugre 3.3 and the third plot on Figure 3.4 that the heading reference, ψ_d have some oscilatory nature. This is because of the relatively low look-ahead distance defined in the guidance algorithm. This can be analogus to when driving a car and you fix your gaze on the road not very far ahead of the car, and you will get more uneasy driving and jerking motion.

The depth reference are given by the bottom which are constructed using a look-up table created by a sinuosidal plane. The reference are followed pretty well. The delay on the action by the controller are created because the *heave* direction are not directley controlled, but are relayed through the *pitch* degree of freedom. This could probably have been reduced by feeding the reference into the controller as well. This will help the controller predict the motion and compensate for it when it happens.

It is worth noting that the *surge* speed overshoots, but is not seen as a problem for further simulation and analysis. The overshoot can be removed by including derivative action in the Speed controller. This would reduce the commanded force when reaching the set point.

2nd Scenario

The environmental forces are now turned. The current is assumed only effective in the North East plane and has no effect in the *heave*-direction. The current is moving from north-west to south-east, heading $-45°$ and have a strength of 0.3 m/s.

In Figure 3.5(a) the search waypoints are shown. The reason for the extra “de-tour” away from the pipeline are because of the short time delay befor considering the pipeline lost. As seen in the first Scenario there are oscilations in the heading reference. This cuases the AUV to drift off the pipeline trajec-

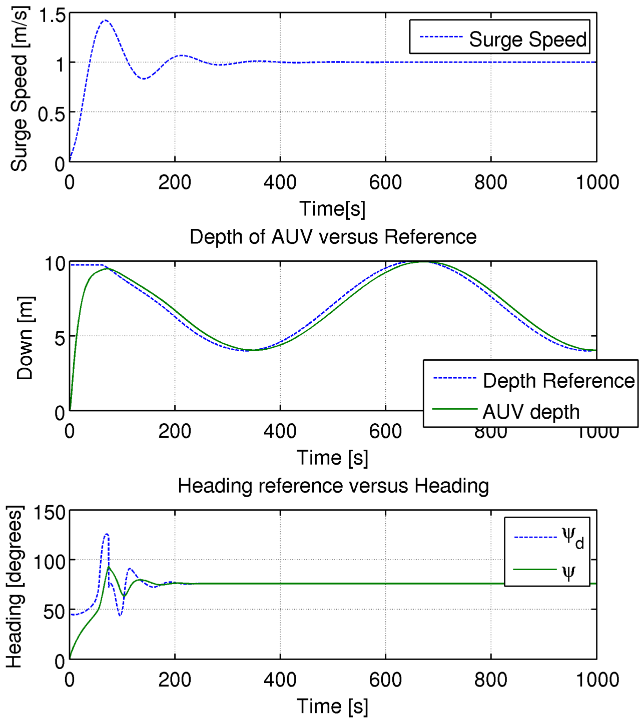
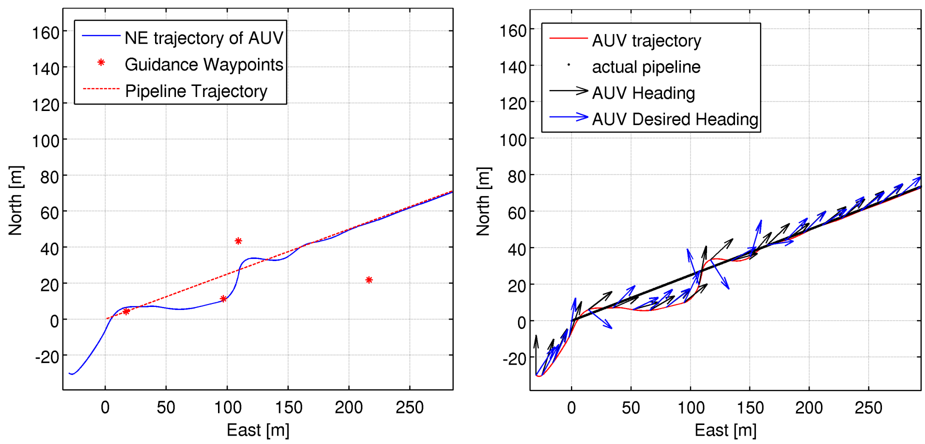


Figure 3.4: Surge-, Depth- and Heading- Reference vs. Actual Values



(a) NE Path with Waypoints

(b) NE path with Heading

Figure 3.5: Plots of the AUV Showing Trajectory, Guidance Waypoints and Heading of AUV second scenario

tory and therefor lose visual contact with it. The system considers the pipeline as lost and generates a search pattern, the “divergent zig-zag” spoken of in Chapter 2.6. The time before going into search mode are set to 25 seconds.

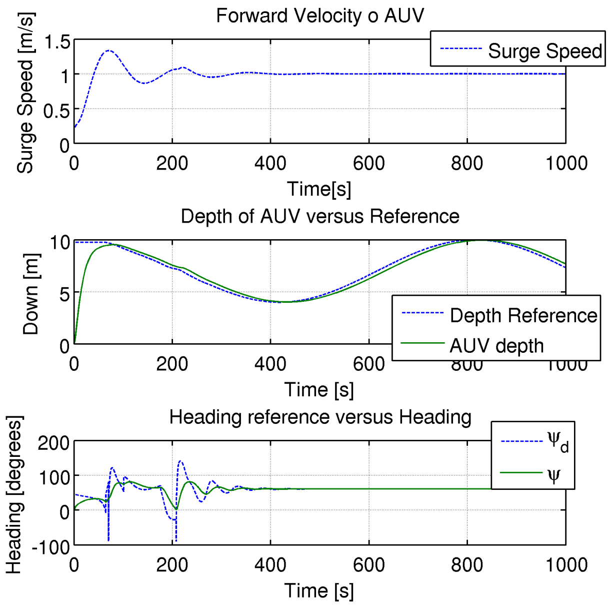


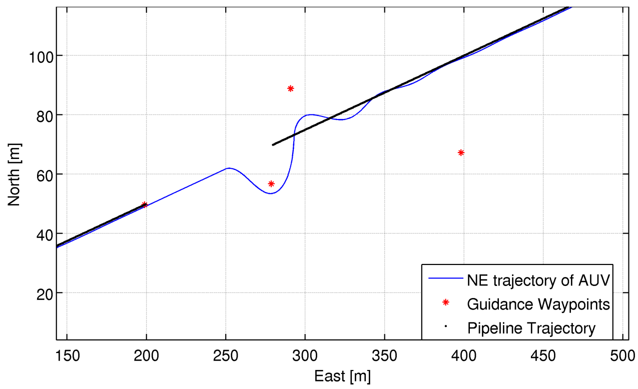
Figure 3.6: Surge-, Depth- and Heading- Reference with Current influence second scenario

When current are introduced the AUV heading are “leaned” toward the current. In Figure 3.5(b) the current are coming from north-west, corresponding to the upper right corner in the figure. This current will try to push the AUV off the pipeline. The guidance system answers this disturbance by adjusting the heading reference towards the current. This is one of the reasons why the lookahead distance are chosen small, because of this the AUV will no drift far away from the pipeline. Since the current is constant, a equilibrium is achieved between the desired heading and the current. The heading converges towards around 60° instead of the pipeline direction of 75°.

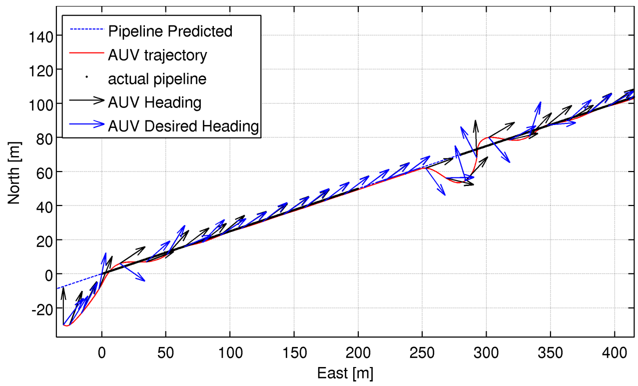
The AUV are not directly on top of the pipeline anymore, but it is not desirable to be exactly over the pipeline all the time. To strictly control the AUV to lay exactly over the pipeline would use up much of the limited power supply. The objective of the AUV are not to stay exactly over the pipeline but to provide good pictures and sensor data for later inspections by humans, because it might be easier to analyse a stable picture than a tightly regulated motion which might cause a noisy picture.

3rd Scenario

The setup for this scenario, is a simulated burrial of the pipeline at apporximtley 50 meters North and 200 meters East. At this point the camera looses track of the pipeline. The guidance system will command the AUV to continue following the predicted pipeline until some time limit are reached. This time limit are set to 60 seconds. From Figure 3.7 it can be seen that the AUV follows the predicted pipeline for about 50 meters and then engages in the predetermined search pattern.



(a) NE Path with Waypoints



(b) NE path with Heading

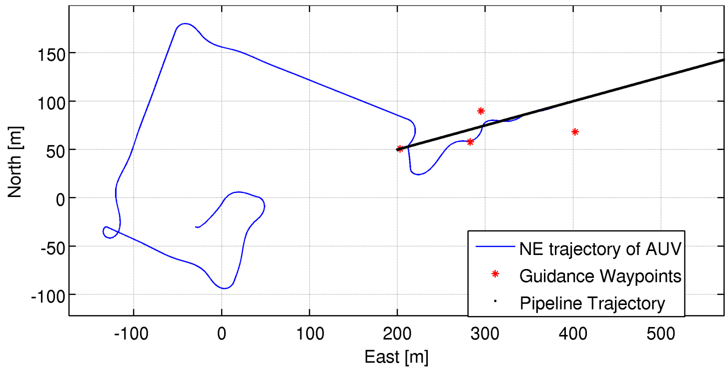
Figure 3.7: Plots of the AUV Showing Trajectory, Guidance Waypoints and Heading of AUV for the 3$^{\text{rd}}$ Scenario

The objective to follow the predicted pipeline is ofcourse to get back on track at the end of the burried strech. Sometimes pipelines are burried on purpose to seal them from environmental erotion, that shorten the lifetime of the pipeline. Sometimes this happens unintended. In either case the need for more sensors which can penetrate the sea bottom and locate the pipeline are needed.

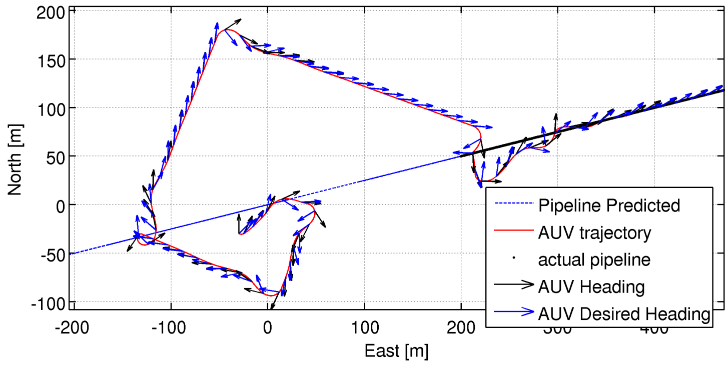
There are no turning trajectory generator implemented at this point, and will not be used in the next scenarios either.

4$^{\text{th}}$ Scenario

The fourth Scenario is to demonstrate the capabilities for the AUV to aquiere the pipeline when it is offset from where it was thought to be.



(a) NE Path with Waypoints



(b) NE path with Heading

Figure 3.8: Plots of the AUV Showing Trajectory, Guidance Waypoints and Heading of AUV for the 4$^{\text{th}}$ Scenario

When the AUV reaches the initial position where the pipeline were ment to be. It does not make contact with it there, then engages in a spiral search pattern. This search pattern are administered by waypoints and the guidance uses the straight lines between the waypoints as the track to follow. This causes the more polygonal look than spiral.

From Figure 3.8 it can be seen that the AUV sometimes takse an extra turn when switching between waypoint four and five. This is due to the calculation of the dersired heading angle. The *matlab*-fucntion, *atan2()* are used which outputs the angle in the domain $(-\pi, \pi)$. Since the output from the AUV model are defined for all values, and this are fed back to the controller a heading reference of 0 means that it must “unwinde” all turns it has done, because this acumulate the yaw value beyond 2π. This is an implementation issue and is not caused by the theoretical guidance system.

The large overshoot when the AUV have located the pipeline are due to the current. This pushes the AUV away from the trajectory. The current increases the velocity in a direction and causes the turning in that direction to be more difficult than turning the other way. This is a problem that is present in all applications involving measurement of heading. One cannot meassure more than one 360° and care must be taken when choseing the reference. This is also a topic in the heading controller. The turn should be taken in the direction that is the shortes or free of obstacles. This is an important part of the control system, but has not been implemented in the current test environment. It becomes an important issue when the turn involves a whole revolution around the z-axis. For a human it is quite obvious which way to turn, but for a non-sentient machine dependent on rules, this becomes an important issue.

The overshoot discussed above is also a product of the relatively large course-changing maneuver. This can somewhat be reduces by using a turn trajectory to get the AUV on the right track and the same direction as the pipeline. This trajectory generation need to handle the problem discussed above regarding the revolution problem.

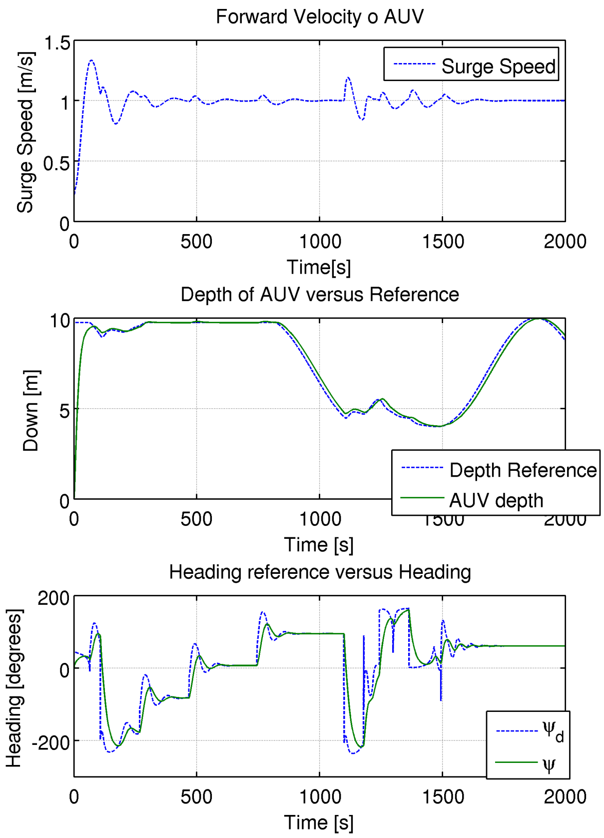


Figure 3.9: Surge-, Depth- and Heading- Reference with Current influence for the fourth scenario

The plots from the velocity, depth and heading references for the fourth scenario, shown in Figure 3.9, are worth noting. It can be seen from the first plot in the figure that during large course-changing maneuvers the surge velocity first gets a overshoot and then decreases under the set point of 1 m/s. This is probably because of the how the current are included in the simulations.

We see that the course changes from around $90°$ to $-200°$ over short time. The surge speed changes correspondingly in the same area. This is becuase when the course angle are about $45°$ the velocity vector are paralell to the current, and at $-45°$ the velocity vector are still paralell but in the oposite direction of the current. this causes the marked changes in the surge speed seen in Figure 3.9. The speed controller cannot anticipate this, and therfore does not ease up on the throttle.

Chapter 4

Discussion

This chapter will summarize and discuss the results in the previous chapter.

4.1 Guidance System

This Guidance system are designed for long, straight pipeline streches. It will not be able to handle sudden turns in the pipeline direction, without spcifying this in the guidance system. This can be included as waypoints where the pipeline are changing, and be included as a condition; *when the AUV reaches certain position the direction of the pipeline changes.* This requiers very exact knowledge about the pipeline and are rearly the case. TThis is why there should be a more autonomous way of doing this. This motivates the use of more sensros than just a camera to follow the pipeline. The camera have a very limited field of view, usually restricted to less than 3 meters. A Side Scan Sonar comined wiht a Forward Looking Sonar, which provides sensor data of the pipeline in front of the AUV will give the guidance system some data to descide and predict what it will do if there is a sharp turn in the pipeline.

Sharp turns are rare, and are a product of T-junctions and other couplings of pipelines. These junctions are usually well documented, and given good and exact locations. But if the navigation sensors of the AUV have large uncertanties, and from the AUV it might look as they are in the wrong place. This suggests that information about the pipeline should be treated with care. Because the errors in an AUV navigation system might be substantial and provide that á priori information about the pipeline will be unusable.

The navigation system of *HUGIN 1000* are a Velocity Aided Inertial Navigation System. This utilises a Doppler Velocity Log to measure the velocity relatively to the sea bottom and input this to the INS system. The INS systems usually installed on the *HUGIN 1000* are in the 1 nmi/h class, i.e the INS system drifts less than 1 nmi in an houre. This results in a drift in the navigation system equal to 0.11 % of the traveled distance along the track, and about 0.03 % error in the across distance of a stright line track according to [JGHV03]. This can be enough to throw the guidance system off course, because the field of view of the camera are relatively small.

There are ways of improving the INS drift and therby improving the position estimate, one is to use GPS update fixes, but this requiers to surface the AUV once in a while. This is of course not a good idea when the AUV are at great depths. There are posibilities to use sea bottom anchored position bouys, which exact position are known and the AUV might use these bouys by pinging them and getting a updated position estimate. This is a good idea if the pipeline infrastructure admints this. Say that this position bouys are placed at the same time as the pipeline are layed, but this is a costly affair.

Too use a Ultra Short Base Line (USBL) are another posibility. A USBL transducer are mounted on a ship, which has a GPS location fix. The AUV then pings the USBL transducer regularily and the position are determined exactly. This requiers a ship stationed in the area where the AUV are carrying out the mision. The autonomicity of the AUV are the reduced, and the vehicle are not capable of operating on its own.

The problem regarding when $\psi \rightarrow 2\pi$ problem as mentioned in the previous chapter is a implemntation issu. There are a number of solutions for this. The first is to limit the sensor output, which is the case in the real world, since a compass measuring *yaw* only are defined for $(0, 2\pi)$. The controller can handle this by including a chech wheter if its heading are larger than π, the given command will be to the right, and opposite if the measured heading are smaller than π.

Increasing the inspection speed

What happens when the inspection speed are increased beyond 1 m/s? Say if the surge velocity were to be increased to 2 m/s.

4.2 Roll Stabilization

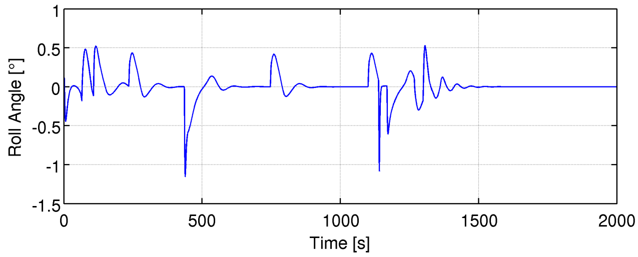
The mission of the AUV are to provide good data for later use, i.e good pictures to be analyzed later. The camera on the AUV are mounted downwards and the field of view are affected by roll and pitch. Pitch are a control angle, but the Roll motion have no direct control measures. The roll angle need to be as close to 0 as possible to provide best pictures of the current sea bottom. The plots in Figure 4.1 are taken from the 4^{th} Scenario described in Chapter 3, to look at *HUGIN 1000* 's stability in roll.

Figure 4.1 shows the relation between commanded yaw moment and the roll angle. Clearly there are coupling effects which causes the roll angle to change a few degrees. The roll angle magnitude are about 2° when the *surge*-velocity are 1 m/s. The values of the *roll* angle are doubled if the velocity are doubled. But the roll angle are not of greate concern when carrying out this kind of inspection missions, as these simulations show.

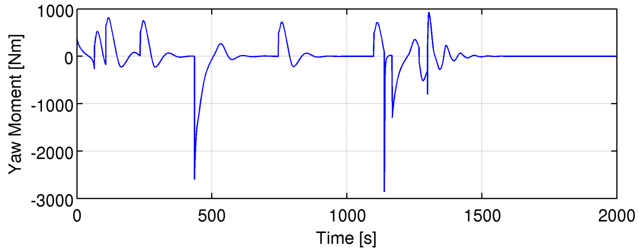
The main propeller gives a moment in roll. This moment are disregarded in the simulations, but might become important. The main propeller are described by the followin relations

$$\begin{aligned} \tau_1 &= T_{nn} n^2 + T_{un} n u \\ \tau_4 &= Q_{nn} n^2 + Q_{un} n u \end{aligned} \tag{4.1}$$

where n are the angular speed of the main propeller in revolutions per minute, and u are again the surge velocity. The second terms in the equation above are terms descibing loss-of-force due to forward speed. The moment in roll are



(a) Roll Angle



(b) Yaw Moment

Figure 4.1: Plots describing the close relation of yaw moment and roll angle

actually countered by weightin the AUV down on one side so that when the it reaches cruice velocity the AUV have zero roll angle. [Gje08]

HUGIN 1000 AUV are designed to be asymptotically stable in roll, due to the centre of bouyancy (CB) are located not exactly in the centre of gravity (CG). The AUV would not need roll stabilisation becuase it shows to be very stable in roll. Another case is that if roll stabilisation were to be implemented it would be done by using the rudders.

4.3 Energy Consumption

The energy consumption of an AUV are of extreme importance. When a customer are buying this type of vessel one of the criteria are operation time. For an AUV which are untethered and have limited power supply the operation time might vary greatly due to installed sensors and operating conditions.

The standard sensor suite on the *HUGIN 1000* AUV are a Side Scan Sonar, Doppler Velocity Log, Depth meter, Multibeam Echosounder, and the INS navigation system. The operation time would be around 10-20 houres, dependent on velocity and sensor use. The main objective of the guidance system after the inpsection part is to maximise the operating time. This can be done in numerous ways, and should be a part of the design procedure when designing the guidance system for the real thing.

The actuator set-up of *HUGIN 1000* are with 4 rudders, one main propeller and 4 thurusters. This renders the AUV controllable in 5 DOFs. The thrusters demand more power than the main propeller and rudders, and have been disregarded throughout this report.

The most energy efficient way of guiding an AUV is to use its main propeller and rudders. But there might be different ways of optimising the power consumption with regard to how the AUV are searching for and tracking the pipeline. The moment produced by for instance the vertical rudders, are proportional to the *surge*-velocity squared.

$$\tau_6 = Y_{u\psi}\delta u^2 \tag{4.2}$$

where δ are the angle of the rudder, and $Y_{u\psi}$ are some constant describing the rudder areal. This means that the effect of the rudders are greatly dependent on the forward speed. This is not taken into account in the designed controller and have to be compensated in a more advanced controller, or it can be taken care of in the control allocation problem not considered in this report.

The energy consumption are very dependent on how the AUV moves. If it are taking unnescecary turns the movemente pattern are not optimal. If the forward speed are taken constant the power consumption will decrease the shorte time it is in flight. In this sense the shortest distance traveled is the most optimal movement pattern. This motivates the designer to make the guidance system to always calculate the shortes path to the goal, if the environment allows it. This opens for a more advanced mode of the tracking system, which the constraint that the AUV should strictly follow the pipeline is relaxed. If sensors like Side Scan Sonar or other sensors with longer range than a video camera are included, these can be used to give good data about the pipeline even if it is not in the camera field of view. The relaxation in the tracking constraints might allow the AUV to move more efficient in terms of energy.

[KU03] proposes an optimal guidance scheme. Using the fuel consumption as a performance index and optimize with regard to the current forces in the area of interest. It requiers knowledge of the currents in the area á priori and utilizes this to calculate the otimal trajectory from one point to the next. This gives good theoretical results but the downside is that knowledge about the current forces in an area are rarely konwn, and if they are known they are probably not very exact. But this scheme might help to save energy, but are only aplicable to a pipeline inspection mission when the AUV are moving to or from the pipeline, not when tracking or searching.

Either way, it is important to chose the right way to go when you have limited power capability. This motivates the use of more sensors, to increase the chances of not giving bad and erronous sensor data to the guidance system. The guidance system needs to be robust and take the right descision. Too maximise the operation time it can not afford to take wrong decisions. This is almost impossible to achieve and can only be done through extencive testing of the complete syste, it is important tto chose the right way to go when you have limited power capability.

***************RANGE**************EQN*********

4.4 Optimal Search Pattern

As discussed above, the need for efficient search pattern are crucial to maximising the operation time. Search patterns might vary form case to case. The search patten should be dependent on how well the mission area are known and how sure one can be about the á priori data about the pipeline condition, sea bottom obstacles and features. Are there obstacles in the area which might be used for position identification and navigation. Or are there obstacles in the area that the AUV should avoid completely, such as mines.

In general the more you know about the mission area, the better can you prepare the AUV for the mission. If there are known features on the sea bottom, those can be used as reference marks and navigation of the AUV. This allows for more customised search pattern which suit the mission area.

4.5 How valid are the results?

The analysis done in this report are ment to be a pre-study of the problems assosiated with this complex pipeline inspection problem. Most of the topics covered in this report need more study to get valid results to how it will work on the real thing. But it shows some key features for a future design.

The distance covered by piplines are large, but most of the pipelines layed today are flexible pipelines and can curve quite a lot, and the asumption about linear pipeline segments are abit to simplifying. On the other hand it is not difficult to generalise the guidance system to consider nonlinear paths.

The visibility is another topic about this simulations. The visibility are quickly degrading as depth increases, and to get good pictures there must have a good source of light. The visibility at 300 meters are probably less than 3 meters. This will greatly decrease the field of view of the camera.

5 Conclusions

In this report the topic of designing a guidance system capable of pipeline inspeciton for the *HUGIN 1000* AUV have been treated. This report have looked at some basics regarding pipeline inspection. A literature study on how pipeline inspection can be preformed was done, and summarised in the report. Some basics about guidance was reviewed.

A proposed guidance system were also designed. The system includes a flight-mode controller, a guidance algorithm and a Kalman filter to fuse measurements and prior knowledge about the pipeline together. The filter will also smooth the output from the sensors to provide a continous reference for the guidance algorithm.

The controller designed are three independent PI-, and PID-controllers. Which were tuned according to stability and simulations.

The behaviour of the guidance system were defined and examined. Some search patterns were discussed, and found that they should be customised with regard to how well the mission area are known and how certain the data about the pipeline are.

The system were implemented in Matlab/simulink and 4 independent simulations were run, demonstrating different abilities with the given guidance system. The system shown results and the given setup worked, also in the presence of ocean current. The simulations were discussed with regard to energy efficiency and pipeline following capabilities. The most optimal path to follow concerning energy optimality when the velocity are constant is the shortest path, in most cases the linear segments between two points.

Whenever the AUV are tracking, the the motion above the pipeline should be constrained to be in the vicinity of the pipeline but not strictly above it all the time. The primary mission of the inspection should be to provide good, easy-to-analyse sensor data which in most cases include trying to maneuver the AUV as smoothely as possible.

The camera should be aided with other sensors, such as Side Scan Sonar and Multibeam Echosounders. Theses sensors help with detection of the pipeline and will also provide data about the condition of the pipeline.

The strict modularity of the guidance system presented in this report allows for easy upgrades and improvment to the different blocks in the system. In further work with this problem the guidance system will be easy to upgrade, with more advanced controllers or guidance algorithms. The simulation environment are present and gives good results, but the control of the system should be better in order to implement in a real application.

5.1 Further Work

As stated before the whole pipeline inspection problem are not treated in a single report. There are much work do be done before this can be transformed into real life application.

First the guidance should handel three dimentional guidance with nonlinear paths. A possible way to do this is to use unified guidance controller proposed in [BF06]. This is a controller for the whole non-zero speed regieme.

The Kalman filter should be designed to include readings from other sensors like Side Scan Sonar, Echosounders, and other possible sensors available for the inspection mission. The filter should be expanded to be capable of three dimentional prediction and a more sofisticated prediction might be used to get good results for the predictions.

- Optimal guidance and path planning

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Appendix: Slightly Important Stuff

A Section

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