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Weather heading estimation

For marine vessels in low speed

Master's thesis in Systems, Control and Mechatronics

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Department of Electrical Engineering
Chalmers University of Technology
Gothenburg, Sweden 2018

Master's thesis EX009/2018

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Cover: Boat with electrical control system from CPAC Systems.

Gothenburg, Sweden 2018

Abstract

Automatic control of marine vessels is a field that has been growing for many years. Currently, there exist many leisure boats equipped with the functionality to automatically stay in a chosen position with a constant heading. This is usually referred to as station keeping and tries to compensate for disturbing forces from weather phenomena such as waves and wind. In commercial applications it is usual to measure properties of the weather forces and use that information to compensate for them during station keeping. However, most leisure boats lack these kinds of sensors.

There exist methods for estimating the weather forces heading by rotating a boat until it faces the weather forces. However, this might not always be possible due to space restrictions in e.g. ports. Therefore, the following question can be posed. Is it possible to estimate the weather forces heading without measuring anything outside the vessel or moving it in a certain way?

Three different methods for estimating the weather heading without affecting the control of the boat are evaluated. All methods are model-based which means that a dynamic model of the boat performing station keeping is required. Such modelling is described and a number of system identification steps to find numerical values for the models are also presented. The proposed system identification steps need to be performed during times when there are little to no disturbances which is undesired.

It was found that varying degrees of system knowledge gave different accuracy in the weather heading estimation. Little knowledge gave a rather weak estimation. The highest accuracy achieved was within about half a quadrant.

Future work can be done to see if it is possible to remove disturbances from data collected at times when disturbances are present to be able to perform system identification at any time.

KEYWORDS: Vessel dynamics, Station keeping, Automatic control.

Sammanfattning

Automatisk reglering av marina fartyg är ett fält som har vuxit under många år. För närvarande finns ett stort antal fritidsbåtar utrustade med funktionaliteten att automatiskt hålla sig kvar i ett valt läge med en konstant bäring genom att kompensera för störande krafter från väderfenomen som vågor och vind. I kommersiella applikationer är det vanligt att mäta väderstyrkornas egenskaper och kompensera för dem under stationering. Många fritidsbåtar saknar dock den typen av sensorer.

Det finns metoder för att uppskatta väderkrafternas riktning genom att rotera en båt tills den står mot nettokraftens riktning. Detta är dock inte alltid möjligt på grund av begränsningar i utrymme, t.ex. som i hamnar. Därför uppstår frågan: Är det möjligt att uppskatta väderkrafternas kurs utan att göra mätningar utanför båten eller styra den på ett särskilt sätt

Tre olika metoder för att uppskatta väderkursen utan att påverka båtens reglering utvärderas. Alla metoder är modellbaserade vilket innebär att det måste finnas en dynamisk modell för båten som utför stationeringen. Sådan modellering beskrivs samt ett antal systemidentifieringssteg för att hitta numeriska värden för modellerna.

Det visade sig att varierande grader av systemkunskap gav olika noggrannhet i uppskattningen av väderkursen. Den högsta noggrannheten som uppnåddes var inom ungefär en halv kvadrant. De föreslagna systemidentifieringsstegen måste utföras under tider då det är lite eller inga störningar närvarande.

Framtida arbete kan göras för att se om det är möjligt att ta bort störningar från data som samlats in när störningar är närvarande för att kunna utföra systemidentifiering vid vilken tidpunkt som helst.

Nyckelord: Automatisk kontrol, Stationshållning, Båtdynamik

Preface

Acknowledgements

I would like to thank CPAC Systems for giving me the opportunity to do this thesis with them, especially my supervisor David Nydahl. Furthermore, I would like to thank my academic supervisor Professor Torsten Wik for providing guidance during the project.

CONTENTS

1 INTRODUCTION

For about a century, development of automatic control in marine vessels has increased. Starting from early autopilots only regulating the heading of the boat to present day where all kinds of autonomous functionality have been developed. A common feature is station keeping or as it is called in the field of research, dynamic positioning.

Dynamic positioning of a marine vessel means that the actuators of the boat are automatically controlled to keep the vessel at a defined point. In the field of automatic control of marine vessels, this has been a subject of research for many years (Sorensen 2011).

The purpose of performing a station keeping operation can vary from deep-sea research project to various tasks in the oil industry, such as loading and unloading a vessel, or for leisure purposes. The challenge of remaining in the same position lies in combating the disrupting forces of nature, such as winds, waves, and current.

Great significance in the quality of station keeping lies in the vessels relative heading to the heading of the disturbance forces. If a ship is pointing perpendicular or directly towards a disturbance force, its ability to counteract this force varies largely in favour of pointing towards the disturbance force. The easier it is to counteract a disturbance force the lower the deviations from the chosen target point and lesser consumption of fuel. However, it is not always desirable, or possible, to point the vessel towards the disturbance force due to limitations in the operation space. Even if it is not possible to position the vessel in an optimal way, it is still of benefit to know the heading of the disturbance forces. It is possible to incorporate this information in the design of the station keeping system to compensate for the weather forces, as shown in (Lei *et al.* 2015). It is common to use sensors to measure the direction and magnitude of forces such as current and wind such (Sarda *et al.* 2017). The cost of adding sensors is negligible in relation to the total cost of a ship. However, there exist many non-commerical smaller vessels equipped with station keeping functionality without environmental sensors. CPAC Systems is a supplier of such systems. To equip all vessels with Cpacs solutions would be costly and time consuming for the supplier of the system. A question to ask then is: Is it possible to compensate for the weather forces in station keeping without explicitly conducting any measurements of such forces? There exist methods for automatically position the vessel in a weather optimal heading, without any environmental sensors (Fossen and Strand 2001). However, as stated it is not always desirable to be in the optimal position as the rotational space of a vessel might be restricted, such as in a port.

There is a method for estimating disturbance forces on a ship described in (Fossen 2000). However, this method depends on profound knowledge of system parameters of the ship, such as hull shape and detailed actuator configuration. The vessels supplied by CPAC Systems vary widely in shape and size. The question is then, is this method applicable on these ships, or is there a need for a new method that operates on limited system knowledge?

1.1 Aim

The aim is to develop and implement new, or extend current methods, to automatically estimate the heading of forces that a marine vessel is exerted to, such as wave, wind, and current forces. The solution should be designed in such a way that the resulting method is functional for as wide range of vessel configurations as possible. With respect to size and types of drive lines and determine the lower limit of system knowledge to be able to accurately enough estimate the weather forces heading. The aim is to produce a solution which can identify the directions of the disturbance forces without having to physically move the vessel into the optimal position but rather determining it by relying on readily available signals in the vessel.

1.2 Limitations

An important distinction to make is that without the ability to separately measure wind and water forces it will not be possible to distinguish them from one and another and thus the result will be the heading of a lumped force vector affecting the vessel. The aim is not to develop new hardware solutions but rather use existing solutions developed by CPAC systems that can provide functionality such as GPS data and heading. Use of any auxiliary equipment not readily available on all boats with digital control systems will be considered an unfeasible solution. However, if it is found that adding sensors such as IMUs to have access to the acceleration of the system would significantly improve the results, it can result in a recommendation to add some sensor in the future. The study will be limited to boats available to CPAC Systems and Volvo Penta in Gothenburg. To validate the generality of any proposed method further testing of different types of vessels is needed. The aim is not to produce a commercial product but rather a proof of concept. The scope does not include evaluation of the possible improvements of station keeping by adding knowledge of external forces.

1.3 Outline of the thesis

The following is a list presenting the main parts of the study, which are discussed in detail below:

- Literature review
- Mathematical modelling
- Method to estimate heading of surrounding forces
- Data collection
- System identification
- Testing and verification

The dynamic behaviour of a marine vessel in water will be described based on previous research including how different weather phenomena such as wind, waves and current forces integrate into the models of vessel dynamics. After establishing a model of vessel dynamics, a review of current existing methods for estimating weather forces direction will be conducted as well as a discussion of their appropriateness for the posed questions and possible modifications that could be made to fit the research questions. The critical system parameters needed to perform estimation of the weather forces heading will be identified and how precise they need to be will be investigated. An emphasis will be put on identifying the disturbance heading based on data collected from real ships performing station keeping rather than identifying on simulated systems with simulated weather effects to be as close to an accurate solution as possible. A number of system identification methods will be evaluated to identify the vessel parameters needed to determine the weather force heading. The performance of the chosen method will be evaluated for different operating and weather conditions as well as tested across a number of boats to ensure generality. The focus is not on implementing a solution in a real-time environment on a commercial boat system but a discussion about implementation aspects will be included. The accuracy and performance of the chosen method will be reviewed. There are a number of performance criterion such as stability of the estimation, how robust is the estimation with regards to sudden changes in the vessels motion, how fast is the converge of the estimation is. It is desirable to have the estimation quickly converge if the vessel moves around or if there is a sudden change in the disturbances. Finally, a discussion about the results and future work will be included.

1.4 Ethical and sustainability aspects

The ethical considerations faced in this research are questions of sustainability. Marine vessels are typically driven by fossil fuels which are inherently bad for the environment. However, since the purpose of the research is to find results that can lower fuel consumption by decreasing movement the negative ethical aspects of working with fossil fuels are balanced.

2 NOTATION

N	North direction
E	East direction
Z	Center of earth direction
x	Surge
y	Sway
z	Heave
ψ	Heading/yaw
$\boldsymbol{\nu}$	State vector
$\bar{\boldsymbol{\nu}}$	Average state vector
u	Surge velocity
v	Sway velocity
r	Yaw velocity
$\boldsymbol{R}$	Transformation matrix between body and inertial coordinate frames
$\dot{\boldsymbol{\eta}}$	State vector expressed in inertial coordinate system
$\boldsymbol{M}$	Mass matrix
$\boldsymbol{M_0}$	Initial guess of mass matrix
$\boldsymbol{C_{RB}}$	Coriolis and centripetal force matrix
d_i	Damping in direction i
d_0	Initial guess of damping
V	Velocity in unspecified direction
$\boldsymbol{\tau}$	Actuator force
$\bar{\boldsymbol{\tau}}$	Average actuator force
$\boldsymbol{\tau_w}$	Weather force
x_g	Distance between center of gravity and body fixed coordinate frame in surge direction
$X_{\dot{u}}$	Hydrodynamic derivative in surge direction
$Y_{\dot{v}}$	Hydrodynamic derivative in sway direction
$Z_{\dot{r}}$	Hydrodynamic derivative in yaw direction
I_z	Rotational inertia in yaw direction
F_d	General damping force
ρ	Water density
V_{rc}	Vessel relative velocity in current
γ_{rc}	Vessel relative heading
λ	Wave length
ξ	Wave elevation
T	Wave period
c	Wave phase
ξ	Wave elevation
ω	Wave angular velocity
t	Time
$\bigtriangledown^2$	Laplace operator
ω	Wave angular velocity
S	Power spectrum
ROA	Response amplitude operator
C_i	Damping constant in direction i

A_F	Front area of vessel
A_L	Side area of vessel
L_{oa}	Overall length of vessel
κ_i	Engine throttle
α	Rudder angle
l	Distance between stern and center of buoyancy
b	Distance from centerline to actuator
K_i	Actuator gain
r_i	Reverse gear factor
$\boldsymbol{F}$	Actuator configuration matrix
p	Setpoint for station keeping
d	Desired distance to setpoint
$\hat{d}$	Actual distance to setpoint
β	Angle to setpoint
J	Objective function
θ	Variable to optimize
θ_w	Weather heading
A_w	First order wave system matrix
$\boldsymbol{f}$	Passive observer state vector
$\hat{\boldsymbol{f}}$	Passive observer estimated state vector
$\tilde{\boldsymbol{f}}$	Difference between measured and estimated states
$\hat{\boldsymbol{\eta}}_w$	Fist order wave force estimator
$\boldsymbol{\nu_w}$	weather velocity states
$\boldsymbol{A}(q)$	Arx model system matrix
$\boldsymbol{B}(q)$	Arx model input configuration matrix
$\boldsymbol{e}(q)$	White noise in Arx model
$offset$	Actuator force at zero throttle
o	Integrated white noise
d_p	desired distance to setpoint
$\hat{d}_p$	Actual distance to setpoint

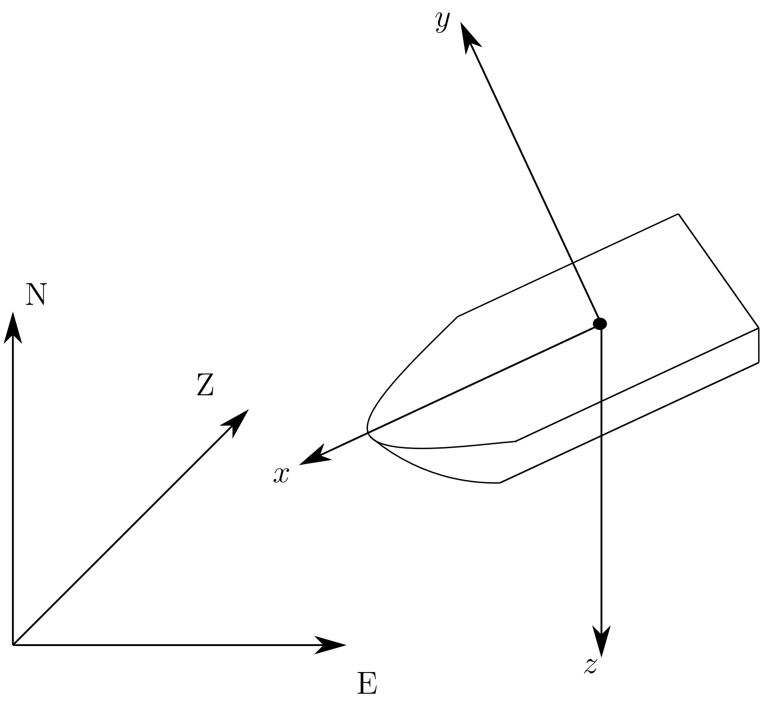

Figure 3.1. Inertial and body coordinate frames.

3 Theory

The models described in this section are largely based on Fossen (2011). This chapter serves to provide an understanding of the movements of a marine surface vessel under influence of actuating signals as well as weather forces. And to provide insight in how to derive the direction of unknown weather forces based on observed movements of a vessel. In the literature, modelling of vessel dynamics largely follow the same framework, where many modifications can be made to fit the purpose of the model. This chapter describes a model made for vessels performing station keeping and is thus a low-speed model.

3.1 Kinematics

With the use of two different coordinate frames it is possible to describe the position and movements of a marine vessel at sea. One earth-fixed coordinate frame and the other is a body-fixed coordinate frame that is moving relative to the earth fixed coordinate frame as can be seen in Figure 3.1. The earth fixed coordinate frame points the Z-axis to the center of earth, the N-axis to the north and the E-axis to the east.

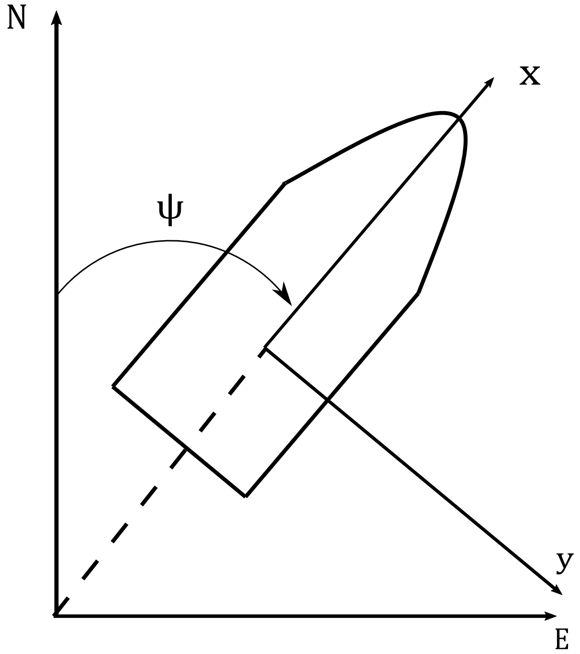

Figure 3.2. Angular relation between the two coordinate frames.

The chosen state vector in the body frame for a model describing the movements of a marine vessel consists of surge, sway and yaw speed. This corresponds to the states $\dot{x} = u, \dot{y} = v$, and the rotational velocity around the z-axis, $\dot{\psi} = r$, which are collected in the state vector $\boldsymbol{\nu}$:

$$\boldsymbol{\nu} = \begin{bmatrix} u \\ v \\ r \end{bmatrix} \tag{3.1}$$

The states can be transformed between the two coordinate frames as follows.

$$\boldsymbol{R}(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.2}$$

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}(\psi)\boldsymbol{\nu} \tag{3.3}$$

Where $\boldsymbol{R}(\psi)$ describes the rotation between the vessel fixed body coordinate frame and the global coordinate frame. Figure 3.2 shows how the heading of a boat links the two coordinate frames together. Equation 3.3 denotes the transformation between the body and earth-fixed frames where $\dot{\boldsymbol{\eta}}$ is the vector describing the vessels movement in the inertial coordinate frame.

3.2 Kinetics

An often referred to equation for modelling a vessel's dynamic behaviour is the equation described by Fossen (2011), i.e.

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C_{RB}}\boldsymbol{\nu} + \boldsymbol{d}(\boldsymbol{\nu}) = \boldsymbol{\tau} + \boldsymbol{\tau}_{wind} + \boldsymbol{\tau}_{wave} \tag{3.4}$$

In the following the meaning and influence of the different terms in Equation 3.4 are elaborated on.

3.2.1 System mass

The so called mass matrix of the system described by Fossen (2011) is:

$$\boldsymbol{M} = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mx_g - Y_{\dot{r}} \\ 0 & mx_g - Y_{\dot{r}} & I_z - N_{\dot{r}} \end{bmatrix} \tag{3.5}$$

The physical mass of a vessel is denoted m and the inertia around the z-axis is denoted I_z. These terms are normally present in most system models, the other terms present in the $\boldsymbol{M}$ matrix arise due to the system moving through water. The term x_g is the distance along the x-axis between the center of the body fixed coordinate system to the center of buoyancy which is point of the body that the vessel turns around.

The remaining terms $[X_{\dot{u}}, Y_{\dot{v}}, N_{\dot{r}}]$ are added mass terms called hydrodynamic derivatives. When a vessel is traveling through water there is friction between the hull and the water adding resistance to the movement. As described in (Palmer 2005) the water particles closest to the hull has the same velocity as the vessel and then outwards there is a velocity gradient with a certain width until the water reaches free stream velocity. This phenomenon can be seen as added mass. There exists a method for approximating the hydrodynamic derivatives called strip theory, though the details are omitted and can be found in Fossen (Fossen 1994).

3.2.2 Centripetal and Coriolis forces

Centripetal forces are forces that are directed towards the center of a circular rotation. The Coriolis effect is a phenomenon arising when a rotating coordinate system observes an object. The earth fixed coordinate system is such a reference due to the rotation of the earth, however, during station keeping the movements of the vessel is relatively small and the Coriolis effect is then small. The expression for these effects is

$$\boldsymbol{C_{RB}} = \begin{bmatrix} 0 & 0 & -m(x_g r + v) \\ 0 & 0 & mu \\ m(x_g r + v) & -mu & 0 \end{bmatrix} \tag{3.6}$$

3.2.3 Damping

All submerged bodies that move in a surrounding fluid experience a resistance to that movement, which is called drag. The general equation for drag is:

$$F_d = \frac{1}{2}\rho V^2 C_d A, \tag{3.7}$$

where C_d is a form factor depending of the shape of the body, and A is the area. The velocity term is quadratic and ρ is the density of the surrounding fluid.

For a marine vessel, the damping can be expressed by the equation below. A_F and A_L are the frontal and lateral area and L_{oa} is the total length of the vessel. For marine vessels, some additional parameters must be considered. V_{rc} is the relative velocity of the body in a current and γ_{rc} is the relative heading of the vessel to the weather forces heading.

$$\boldsymbol{d}(\nu) = \begin{bmatrix} -\frac{1}{2}\rho A_F C_X(\gamma_{rc}) V_{rc}^2 \\ -\frac{1}{2}\rho A_L C_Y(\gamma_{rc}) V_{rc}^2 \\ -\frac{1}{2}\rho A_L L_{oa} C_N(\gamma_{rc}) V_{rc}^2 \end{bmatrix} \tag{3.8}$$

3.3 Environmental forces

This section serves to provide a theoretical view of how environmental forces such as waves and winds affect the behaviour of a marine vessel.

3.3.1 Wave forces modelling

The dynamics of waves, as illustrated in Figure 3.3, can be described by the following parameters:

- Wave length: λ
- Wave period: T
- Phase velocity: $c = \frac{\lambda}{T}$

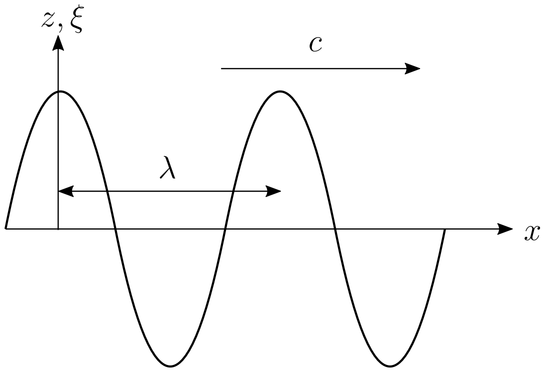

Figure 3.3. Wave propagation in one dimension

- Wave elevation: ξ

The wave dynamics can be analytically expressed by the following partial differential equation.

$$\frac{\partial^2 \xi}{\partial t^2} = c^2 \bigtriangledown^2 \xi \tag{3.9}$$

In reality, the behaviour of ocean waves is nonlinear and turbulent. To get a more realistic model, different wave frequencies can be superimposed into wave patterns that behave more realistically. The distribution of power across frequencies in a signal is a called power spectrum. The topic of creating power spectra that are realistic has been studied extensively; one example can be seen in (Fossen 2011).

Naturally, a ship's response to waves is highly dependent on the geometry of the ship. For industrial ships, it is common to use advanced software programs to calculate ship responses in waves specific to the geometry of the ship's hull by linking the wave amplitude from the wave spectrum to a response amplitude operator (ROA) that translates the wave amplitude to a force τ_{wave}.

The forces a marine vessel is exerted to from waves can according to Fossen be split into two parts. First order forces that are oscillatory and second-order forces that are not oscillating and changes slowly. The first order forces contribute to roll and pitch motions, and the second order forces contribute to surge and sway motions. In station keeping the second order forces are much more important than the first order forces.

According to the same source, one possible simplification of the second order wave forces, which removes the dependency of hull geometry, is to use a generic linear second order system excited by white noise.

$$\tau_{wave} = \frac{K_w s}{s^2 + s\lambda\omega_e s + \omega_e^2}\omega_i + o_i \tag{3.10}$$

The term o_i is integrated white noise and represents a slow change in the dynamics corresponding to the possible change of weather conditions over time. This model is far simpler to implement in computer simulations than Equation 3.9.

3.3.2 Wind forces modelling

Wind is a natural phenomenon where gases in the earth's atmosphere move when different conditions are met. When wind hits the hull of a marine vessel, forces arise that are dependent of the shape of the hull as well as the vessels orientation relative the heading of the wind.

Wind can be expressed in a similar way to how damping forces are modelled and also simplified according to (Fossen 2011).

$$\boldsymbol{\tau}_{wind} = \frac{1}{2}\rho V_r^2 \begin{bmatrix} C_x(\gamma)A_F \\ C_y(\gamma)A_L \\ C_z(\gamma)A_L L_{oa} \end{bmatrix} \tag{3.11}$$

The coefficients C_i are constants dependent of the shape of the hull. They can be approximated with the following expression.

$$C_x(\gamma) \approx -c_x \cos(\gamma_w) \tag{3.12}$$
$$C_y(\gamma) \approx -c_y \cos(\gamma_w) \tag{3.13}$$
$$C_z(\gamma) \approx -c_z \cos(\gamma_w) \tag{3.14}$$

. Where the constants c_i are somewhere in the range of $c_i \in [0.05, 1]$. Accurate modeling of wind forces demands on accurate knowledge of vessel properties. They can either be determined by controlled experiments, numerical simulations or approximations such as equation 3.12.

3.4 Actuator model

For a dual propeller actuated vessel, the free body diagram of the produced forces can be expressed as in Figure 3.4. The resulting forces can be written as

$$\boldsymbol{\tau} = \boldsymbol{r_i F}(\alpha_i)\boldsymbol{K}\kappa_i + \boldsymbol{offset}, \tag{3.15}$$

where κ_i is the individual throttle of each drive-line and α_i is the rudder angle. K_i is the gain of the actuator.

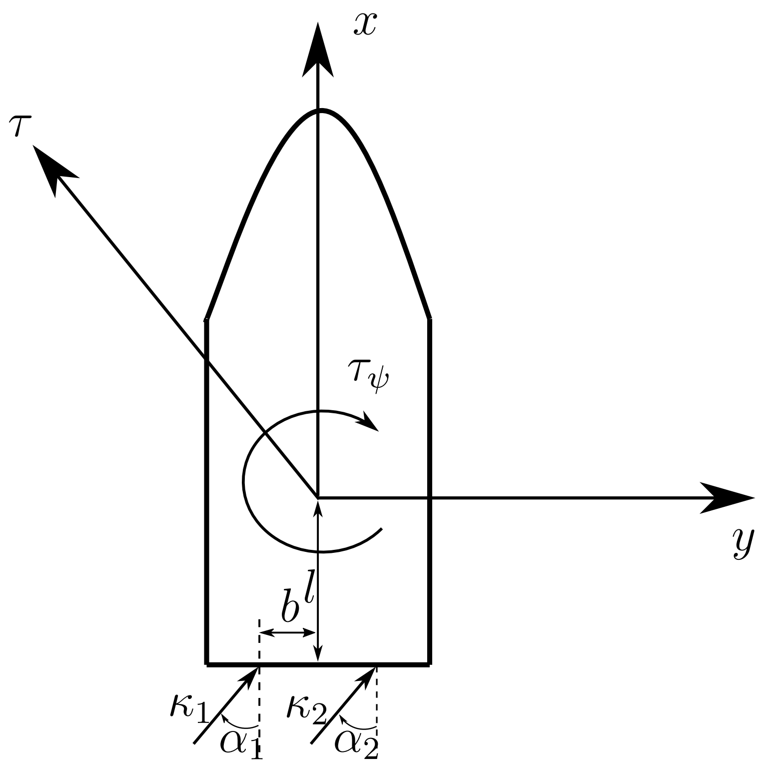

Figure 3.4. Actuators located at the stern produce a force vector $\boldsymbol{\tau}$.

The full equation for $\boldsymbol{\tau}$ written as

$$\begin{bmatrix}\tau_x\\ \tau_y\\ \tau_\psi\end{bmatrix} = \begin{bmatrix}r_i\\ r_i\\ 1\end{bmatrix} \cdot \left(\begin{bmatrix}\cos(\alpha_1) & \cos(\alpha_2) & 0\\ -\sin(\alpha_1) & -\sin(\alpha_2) & 0\\ \cos(\alpha_1)b + sin(\alpha_1)l & -\cos(\alpha_2)b + sin(\alpha_2)l & 0\end{bmatrix} \begin{bmatrix}K_1\kappa_1\\ K_2\kappa_2\\ 0\end{bmatrix} \right) + \begin{bmatrix}offset\\ offset\\ 0\end{bmatrix}. \tag{3.16}$$

The term r_i has been added as a factor to describe the loss of produced thrust when the propellers turn in a backward direction. There has also been an offset corresponding to the idle speed added to the actuator function due to when the engine is running and forward or backward gear is engaged, the propeller is connected to the engine shaft and turns even if there is no throttle and thus produces a thrust.

The thrust equation is nonlinear but the gain of the model is chosen to be linear (see Figure 3.5). Despite that the output power of a combustion engine is well known to be non-linear, which can be seen in for instance (Van Basshuysen and Schäfer 2016). Since specific engine data is unavailable, though, the engine model is here simplified to be linear.

Accurate calculations of propeller thrust depend on the knowledge of exit velocities at the propeller, which in relative high forward speed can be assumed to be equal to the speed of the vessel according to (Carlton 2012). These assumptions are not

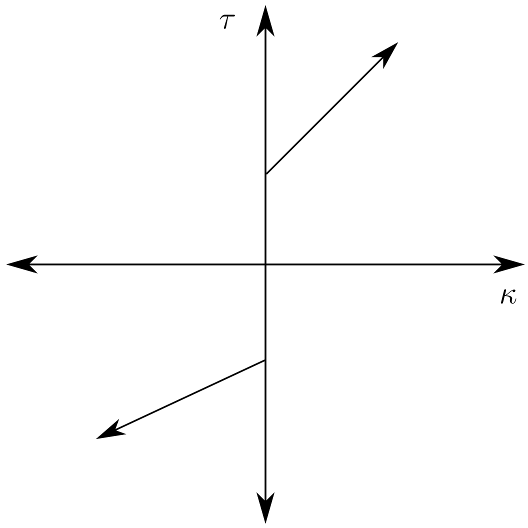

Figure 3.5. Actuator gain function.

possible in zero speed or low forward speed applications, where the current water velocity is similar to the vessels velocity.

A practical solution to estimate the thrust is, according to (Fossen 2011), to assume a linear model. To find the gain of the actuator model, system identification can be used.

3.5 Methods for identifying disturbance heading

This chapter describes methods for estimating the weather heading by physically moving the boat into the optimal heading. It is included to serve as a guide to alternative solutions that solve the problem of finding the weather force heading. There are cases when it is not desirable to move the vessel against the force field, but if those cases are of no concern this chapter presents solutions that might perform better than the methods implemented in this project.

3.5.1 Weather optimal heading control

A popular method by (Fossen and Strand 2001) is called weather optimal heading control and consists of viewing the vessel as a pendulum where the weather forces act as the gravity. To move the vessel into the optimal heading an arbitrary point p in the NE-plane is chosen as well as a distance to the point d, which corresponds to the length of a pendulum(see Figure 3.6 for an overview). The goal of the control system is then to point the heading of the vessel towards the point, such that the

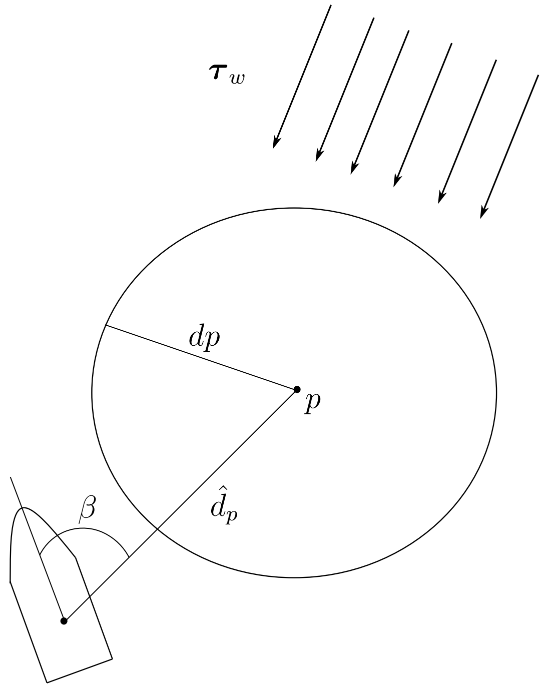

Figure 3.6. Weather optimal heading control method visualised.

angle to the setpoint β goes to zero, and to control the surge of the vessel to keep the actual distance $\hat{d}_p$ to desired distance to the point, d_p. The force field $\boldsymbol{\tau}_w$ acting on the vessel will push the vessel into a heading which faces the force field. A direct analogy to attaching a weight to a string and releasing it with an angle to the ground and letting the gravitational force pull it down towards the floor. Varying lengths of the pendulum produces different results. As shown by (Kjerstad 2010) a longer pendulum results in a longer travelled distance but a shorter pendulum has a higher risk of suffering from overshoot.

3.5.2 Pure rotation into the optimal heading

An alternative idea would be to rotate the vessel without any other movements and for each degree turned evaluate some performance criteria. Naturally, when rotating with the current it will become easier to rotate until an extreme point is reached and then it is known that this heading is pointing away from the weather forces. The same principle would be applicable when rotating against a stream. A recently published paper (Zhang *et al.* 2017) explores an alternative approach to the problem by using extremum seeking method. The advantage of this algorithm is that the optimization can be done without explicitly measuring the variable that is being optimized. Instead, some other available signal can be used. Figure 3.7 visualizes the method, and (Zhang and Ordónez 2005) describe the method in detail.

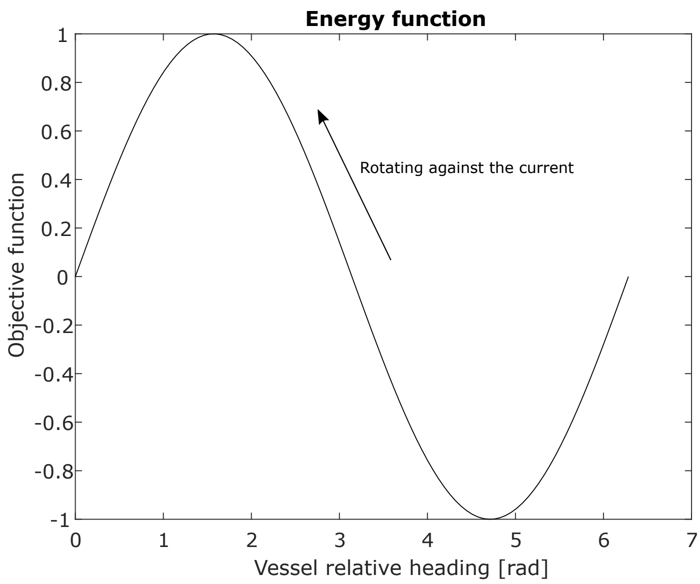

Figure 3.7. General shape of the energy function for rotating a vessel.

4 Method

This chapter describes each step in the methods used to estimate the heading of the weather forces. The boat used during the experiments were a 30 feet leisure boat equipped with two 250 horsepower outboard engines. The state vector is limited to three degrees of freedom: Surge, sway and jaw speed corresponding to u, v and r, which can be seen in Figure 3.1. Heave, which is translation along the z-axis, is neglected. The reason is that there is typically not any readily available measurement of heave as well as that this state is not significant in station keeping performance. To simplify, roll and pitch are neglected as well.

In order to perform station keeping with any heading, a vessel has to produce independent forces in surge, sway, and jaw. When a system has m inputs and n states it is fully actuated if $m \geq n$, according to Pettersen and Fossen (2000). This is the reason for the choice of actuator setup and state vector. If full actuation is not possible the methods described in Section 3.5 might still be applicable.

A number of experiments were conducted. Trial runs were made under different operating conditions with the purpose of system identification and station keeping functionality with different orientation relative to the disturbance heading, as well with the purpose of recreating the disturbance force heading with post calculations.

The measured signals during the experiments were:

- α_i: Rudder angle of starboard and portside engines
- κ_i: Throttle percentage of starboard and portside engines
- ψ: Compass heading
- u: Surge velocity
- v: Sway velocity

4.1 System identification

If all parameters discussed in the theory chapter was known the following equation would solve the problem:

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C_{RB}}\boldsymbol{\nu} + \boldsymbol{d}(\boldsymbol{\nu}) - \boldsymbol{\tau} = \boldsymbol{\tau}_{weather} \tag{4.1}$$

The following describes a gray-box method for identifying a system model. The approach is to perform a number of manoeuvres that will cancel out some parts of the system dynamics allowing estimation of certain parameters. It is crucial that the experiments are done on as calm of a day as possible to minimize the disturbances that would degrade the estimations, or alternatively, use some sensors that can measure the heading and velocity of wind and currents during the identification manoeuvres.

4.1.1 Identification of actuator parameters

By starting with some initial guesses of the most significant system parameters; $\hat{\boldsymbol{M}}_{\mathbf{0}}, \hat{\boldsymbol{C}}_{\mathbf{0}}$ and $\hat{\boldsymbol{d}}_{\mathbf{0}}$, and conducting the following experiments an initial estimation of the actuator offset and gain can be made.

By going straight forward with no surge and constant velocity there will be no or close to zero acceleration $\dot{\boldsymbol{\nu}}$ and the Centripetal and Coriolis matrix $\boldsymbol{C}_{RB}$ will be zero as well. The remaining non-zero terms in equation 4.1 will be

$$\hat{\boldsymbol{M}}_{\mathbf{0}}\dot{\boldsymbol{\nu}} + \hat{\boldsymbol{d}}_0(V) = \boldsymbol{\tau}. \tag{4.2}$$

It is then possible to solve equation 4.2 for the gain. With zero throttles and a gear engaged in both actuators, it is possible to find the offset in the actuator model. Both forwards and backwards gear offsets need to be identified.

To estimate the reverse gear factor r it is assumed that it is the same for all installed drivelines on the boat. Engage backwards gear on one driveline and forward on the other. Direct the desired thrust on the boat directly toward starboard or port side and tune the r parameter in Equation 3.15 until the following expression holds:

$$\frac{\pi}{2} = atan2(\tau_y, \tau_x). \tag{4.3}$$

Where the $atan2$ function is the arctangent with the added ability to distinguish between which quadrant the angle lies in.

4.1.2 Identification of rigid body parameters

After identifying the actuator parameters the next step is the identification of rigid body parameters, mass and drag coefficients. As mass and drag will always be present in the dynamic behaviour it is not possible to separate them. However, some measures can be taken to achieve a reasonable estimation of their properties.

The first step is to perform another manoeuvre. By accelerating from zero velocity to about a couple of meters per second in the surge direction, the mass matrix is introduced into the system dynamics. An uncertainty that arises is the fact that the acceleration is unavailable for measurement. However, with a constant acceleration in one direction, it is possible to numerically differentiate the velocity and get a decent estimation of the acceleration.

Linear trends can be removed from the data to increase the accuracy in the identification. If introduced $\bar{\boldsymbol{\nu}}$ and $\bar{\boldsymbol{\tau}}$ are the average values of the state and actuator force vectors.

$$\Delta\boldsymbol{\nu} = \boldsymbol{\nu} - \bar{\boldsymbol{\nu}} \tag{4.4}$$

$$\Delta\boldsymbol{\tau} = \boldsymbol{\tau} - \bar{\boldsymbol{\tau}} \tag{4.5}$$

Using these deviation parameters it is possible to set up two equations,

$$\boldsymbol{M}_0\Delta\dot{\boldsymbol{\nu}} + \boldsymbol{d}_0 = \Delta\boldsymbol{\tau} \tag{4.6}$$

and a simulated system were the input to the real system has been used to actuate an open loop simulation, i.e,

$$\boldsymbol{M}_0\Delta\dot{\hat{\boldsymbol{\nu}}} + \boldsymbol{d}_{\mathbf{0}}(\Delta\hat{\boldsymbol{\nu}}) = \Delta\boldsymbol{\tau}. \tag{4.7}$$

Now it is possible to do a least square fit of the simulated velocities and use the mass as a parameter.

$$J(m) = \sum_{j=x,y}^{2}\sum_{i=1}^{N}(\Delta\nu_j(t_i) - \Delta\hat{\nu}_j(t_i))^2 \tag{4.8}$$

$$\hat{m} = \hat{\theta} = arg\ m\ J(m) \tag{4.9}$$

An increased accuracy in the model parameters has now been achieved if the rotational velocity is zero. The remaining untouched parameter is the damping vector $\boldsymbol{d}$.

A possible evaluation of the model accuracy is to perform another sea-trial. With another surge motion, this time under conditions where notable disturbance forces are present. Steer the vessel directly towards the disturbing force field one time and another time where the vessel is steered away from the disturbing forces. Perform a pair of open loop simulations with the same input to the system as in the performed sea trials. If the model is accurate enough for the case of operating against the weather, the simulated system without any disturbance forces should be ahead of the real system. In the other case, where the real vessel is being pushed forwards by the weather forces, the simulation should be lagging (see Figure 4.1 for an illustration). The solid boat is the real boat and the dashed boat is the simulated model. If an undesired behaviour is observed it is possible to tune the damping parameters until the desired behaviour is achieved. The same can be done while going sideways in negative and positive sway direction. And the same for going backwards i.e in negative surge direction to estimate these damping terms.

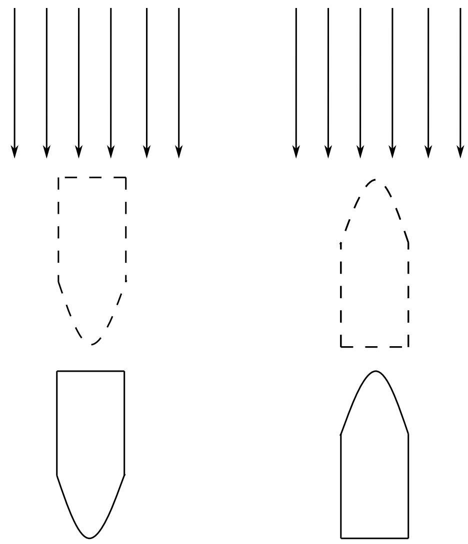

Figure 4.1. Two manoeuvres for evaluating correctness of the system model.

4.2 Nonlinear passive observer

One method to estimate the weather force heading is a nonlinear passive observer, a method developed by Fossen (2000). This method was, according to Fossen designed as an alternative to using the Kalman filter as a predictive method of a vessels position (see Figure 4.2 for an overview of the method).

The method is based on minimizing the difference between the movement of a vessel predicted by a system model, and the actual movement measured by sensors, such as a GPS and a compass. The method collects the difference between the model simulation and the measurements into a bias ($\boldsymbol{b}$) estimator. This bias estimator contains the dynamics associated with current forces, wind and wave forces. Additionally, there is a vector $\hat{\eta}_w$ that can be added to compensate for first order dynamics of waves as described in Section 3.3. This first order wave estimator was neglected due to roll and pitch states not being considered significant. There are a number of gains that can be tuned until satisfactory results are obtained. The bias vector is formulated in the inertial coordinate frame and considers the three states: surge,

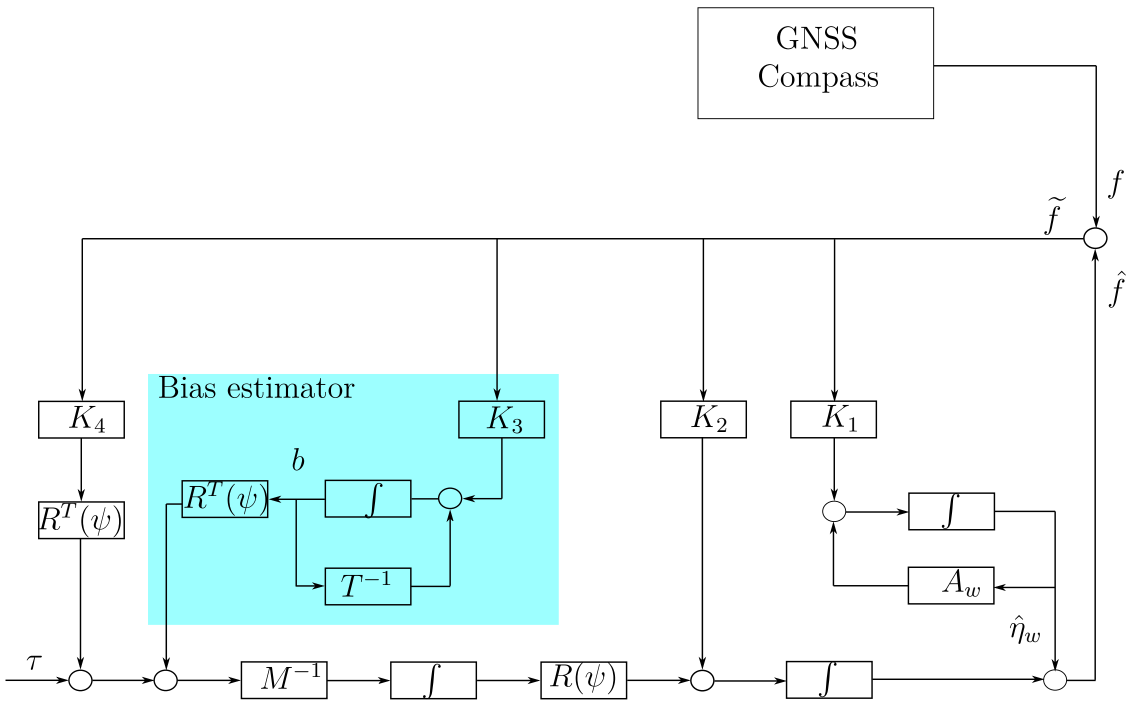

Figure 4.2. Nonlinear passive observer adapted from (Fossen 2000).

,

sway, and jaw. Any model inaccuracies will be included in the the bias estimator.

To estimate the heading of these disturbances one takes the argument between the surge and sway bias estimate.

$$\theta_w = atan2(b_y, b_x) \tag{4.10}$$

4.3 Disturbance velocity method

The method described above has some disadvantages. Firstly there are a number of gains that need to be manually tuned. Then it is also based on estimation of the acceleration of the system, which is difficult. An alternative simplified approach is the following.

While performing the station-keeping manoeuvre, simulate the model in open loop with the same actuation signal as the real system, i.e.

$$\boldsymbol{M}\dot{\hat{\boldsymbol{\nu}}} + \boldsymbol{d}(\hat{V}) = \boldsymbol{\tau}. \tag{4.11}$$

Instead of estimating the disturbance forces $\boldsymbol{\tau}_w$ and try to find a heading from that term, a simplified approach is to look at the difference in velocity between the real system and the simulation. If there were no model inaccuracies and no disturbances, $\boldsymbol{\nu}$ and $\hat{\boldsymbol{\nu}}$ would be equal. The difference is determined as the average over a sequence of N samples, i.e.

$$\boldsymbol{\nu_w} = \frac{1}{N}\sum_{n=1}^{N}(\boldsymbol{\nu}(n) - \hat{\boldsymbol{\nu}}(n)) \tag{4.12}$$

Finally, the heading of the disturbance force can be estimated by taking the argument between the difference in the x and the difference in the y-direction. Figure 4.3 shows the difference between the simulated model and the real ship.

$$\theta_w = atan2(\nu_{w_y}, \nu_{w_x}) \tag{4.13}$$

4.4 Black box modelling

An alternative way to model marine vessels dynamics is to use models that has little or no physical meaning in the parameters. Such methods are described in (Berretta *et al.* 2013). The advantage is that the model is less complicated but a clear disadvantage is that the time of sea trials that have to be performed to collect data for identification is much longer, which increases the risk of having a change in disturbances. The reason why more data must be collected is that all possible dynamics associated with station keeping need to be captured in order to create a model that behaves as realistic as possible. It is much more crucial that weather disturbances are low during the data collection for identification as it is not as easy to compensate for weather forces by using the previously described models. The following is a brief explanation of modeling described in (Ljung and Glad 2016). The goal of the model is to map a relation between throttle and rudder angle to surge and sway in an easy was as possible.

The chosen black box model is a linear ARX model on the form

$$A(q)y(t) = B(q)u(t) + e(t). \tag{4.14}$$

The input is chosen to be $u(t) = \tau(t)$, where the gain in the actuator function has been set to 1 and y is the velocity of the system. The reason is that the strongest non-linearity i.e. the rudder angle is easy to separate from the rest of the model and the reverse gear factor is identifiable with one manoeuvre.

The Arx model is chosen to be a MIMO system with two inputs and two outputs. The reason is to capture dynamics that couples the surge and sway states. As shown in Chapter 3 the system is nonlinear but the ARX model is linear. As the damping is quadratic with respect to the velocity, this simplification could be reasonable at low speeds.

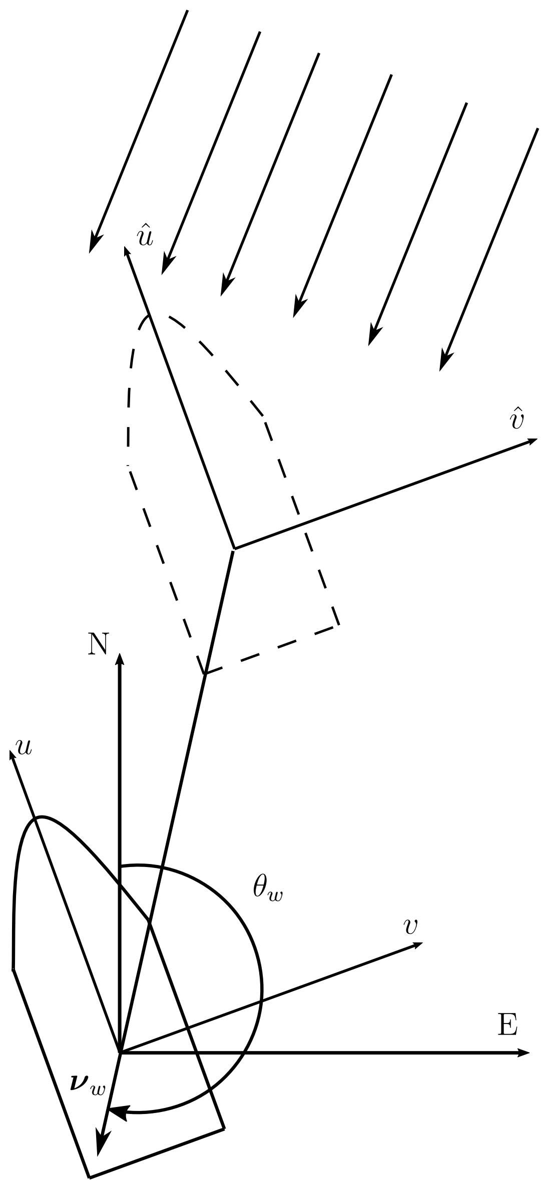

Figure 4.3. A real ship influenced by weather forces compared to a simulated model.

By performing a series of step responses by changing one input at a time, for example beginning with a change in throttle and waiting until the step response has settled, then do this for all possible inputs then most of the dynamics of the system would bee captured. Such a method is described in (Berretta *et al.* 2013).

4.5 Recursive estimation

To have a more stable estimation less sensitive to sudden changes, such as a strong gust of wind or wakes from a bypassing vessel, it is possible to use the recursive least square algorithm. Since it is two constants in a first order system that is being estimated it is not a difficult implementation. The details of the RLS algorithm are omitted and can be found in (Diniz 2008).

4.6 Correctness check

There are some possible ways of checking if the estimation is reasonable. If the distance between the centerline and actuators and distance between the stern and center of buoyancy are known, it is possible to compute the applied torque τ_ψ from the actuators as described in Equation 3.16. If the applied torque is zero or oscillating around zero, it can be assumed that the vessel is facing or facing away from the weather forces.

Another way of checking if the solution is reasonable is to calculate the mean heading of the applied force in the xy-plane in the body frame during station keeping. It is reasonable to assume that over time the applied forces of the boat will converge into the opposite of the weather forces heading.

5 Results

The results presented in this chapter are based on three sea trials. Station keeping was activated twice, once where the heading of the boat was facing toward the disturbance force field and once where the boat was rotated a quarter of a circle as shown in Figure 5.1. The third experiment used the models identified for one boat on a bigger boat to see how general the dynamics of a boat is. The heading of the weather disturbance was estimated by rotating the boat until it was facing directly towards the current and the compass heading was manually read. For an in-depth visualization and comments on the data used see Appendix A. The first two experiments were conducted on the same occasion with identical weather conditions. The experiments were conducted inside a bay just outside Gothenburg. Due to lack of equipment, no measurements were taken on the weather conditions. By using the Beauford wind scale explained in (Beer 1983) the wind speed was ocularly estimated to be between about 1 to 2 meters per second by estimating the height of the waves and translating to wind speed by the Beauford scale. By letting the boat drift with zero input the total disturbance velocity was estimated to be about 1.5 meters per second. The wind was estimated to have about the same heading as the waves.

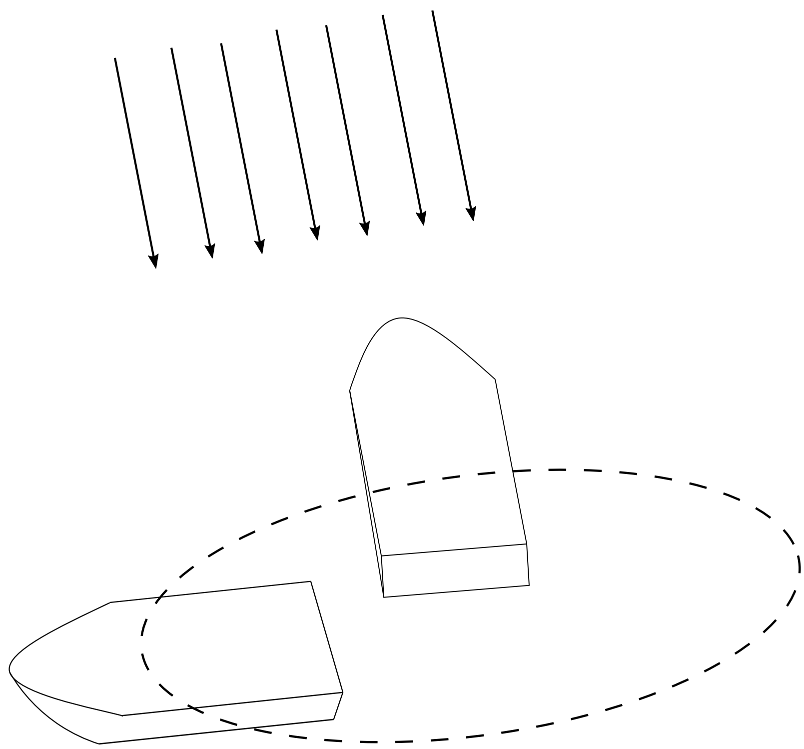

Figure 5.1. Experiment configurations.

5.1 Comparison with trivial solution

Since station keeping serves to keep a vessel in a fixed position it is natural that the actuators would try to counteract the weather forces trying to push the vessel away. By taking the argument between the applied forces in the surge and sway direction an actuator force heading τ_θ can be calculated. Figure 5.2 shows the calculated heading for both the case where the vessel was facing away from the weather forces and when the vessel is facing the weather forces. τ_θ is shown where the identified actuator gain has been set to 1 as to remove any system identification parts. To get the weather heading estimation it is possible to simply add 180 degrees to the actuator force heading and the result would be within about 40 degrees.

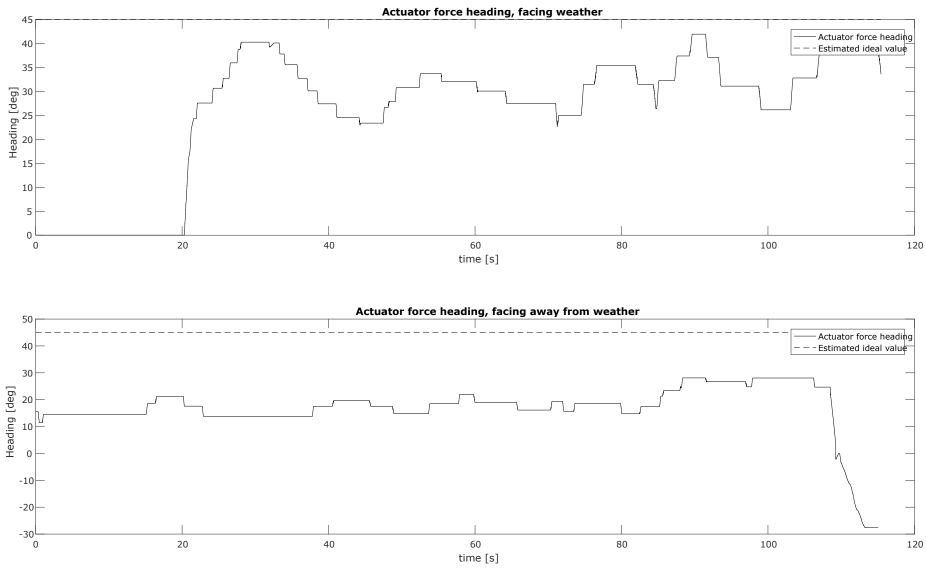

Figure 5.2. Actuator force heading for facing the against and away from the weather forces.

Depending on what tolerance is desired it might be worth to investigate if the dynamic position solution gives a consistent under- or over-estimation between all heading configurations and between different boats. If consistent it could be compensated for and then an accurate enough solution might have been found.

5.2 Facing away from weather force field

The position of the boat can be seen in Figure 5.3. The heading started at zero degrees and in about 15 seconds rose to and remained slightly oscillating around 45 degrees during the whole test duration. The boat was initially pushed backwards and downwards by the weather forces before the regulator was activated.

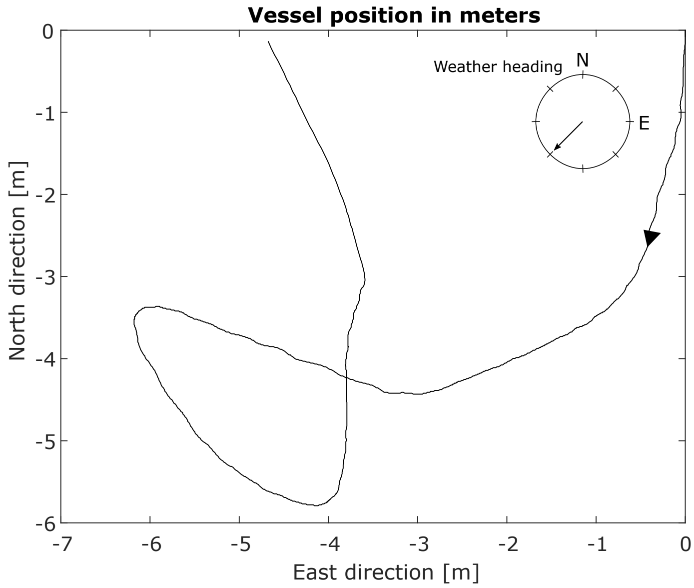

Figure 5.3. Vessel position in inertial coordinate system.

In Figure 5.4 the performance of the non-linear passive observer for the test case can be seen. The rise time was just short of a full minute which is slow compared to the other methods. Despite some overshoot and subsequent oscillations around the estimated true heading, the result was very stable compared to the other methods.

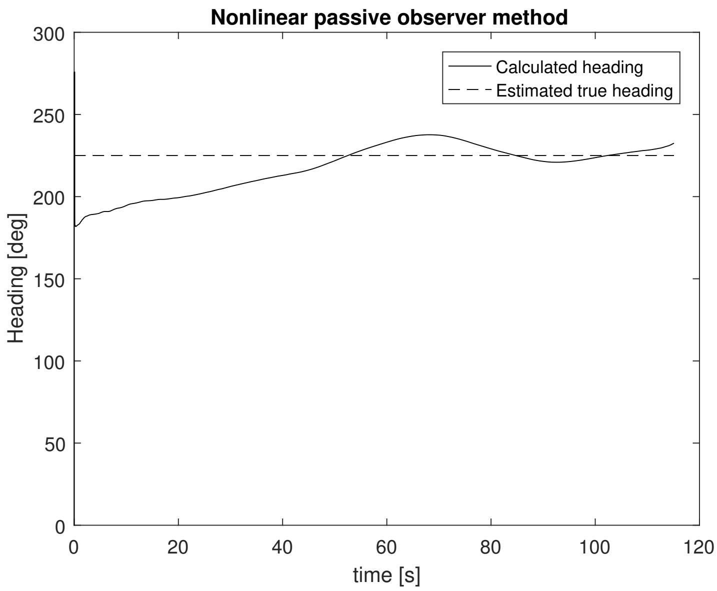

Figure 5.4. Estimated weather heading by the passive observer.

Out of, the methods used, the method of estimating a disturbance velocity was the most effective. As seen in Figure 5.5 the time of reaching an estimate within half of a quadrant was a few seconds. The results have oscillations with both high and low frequencies which could be smoothed out with a notch filter.

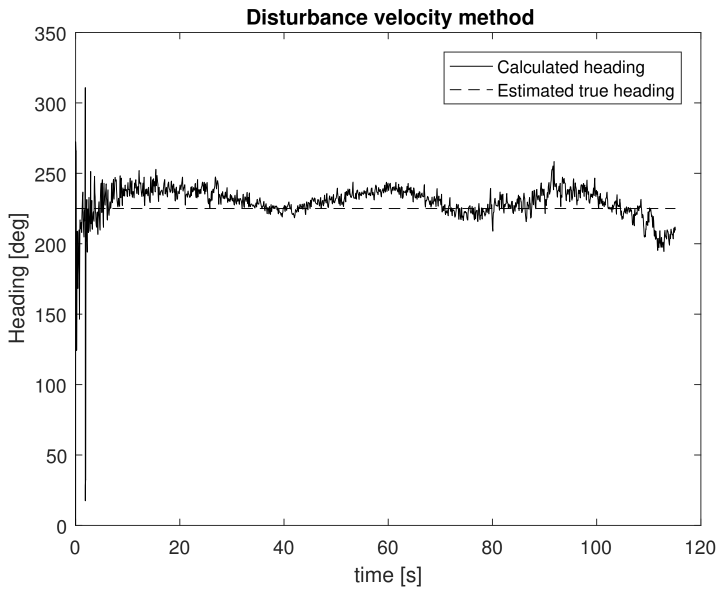

Figure 5.5. Estimated weather heading by the disturbance velocity method.

The third method, a black box model consisting of a two input and two output ARX model seen in Figure 5.6. This result was slightly worse than the previously mentioned method with a larger amplitude in the low-frequency oscillations.

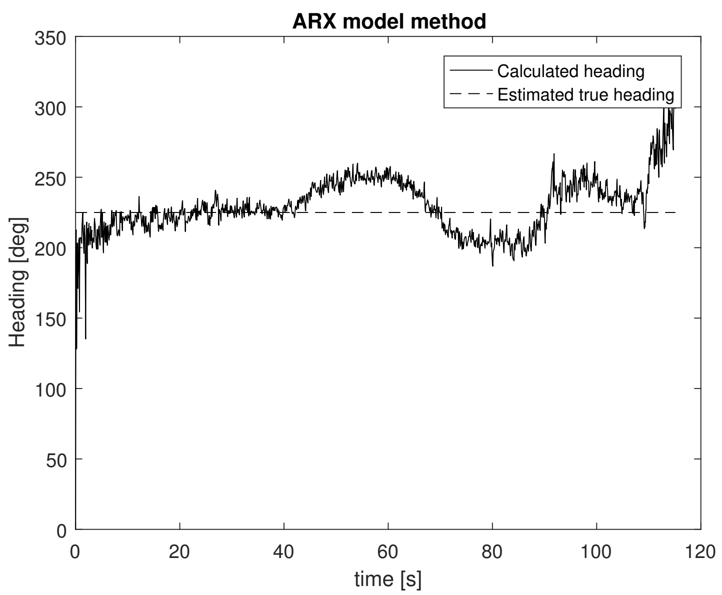

Figure 5.6. Estimated weather heading by the Arx model.

5.3 Facing the weather force field

The second test case where the boat was facing almost directly towards the weather force field with a small observed overshoot in heading. In this case, the boat travelled in an arch around the chosen set point as seen in Figure 5.7.

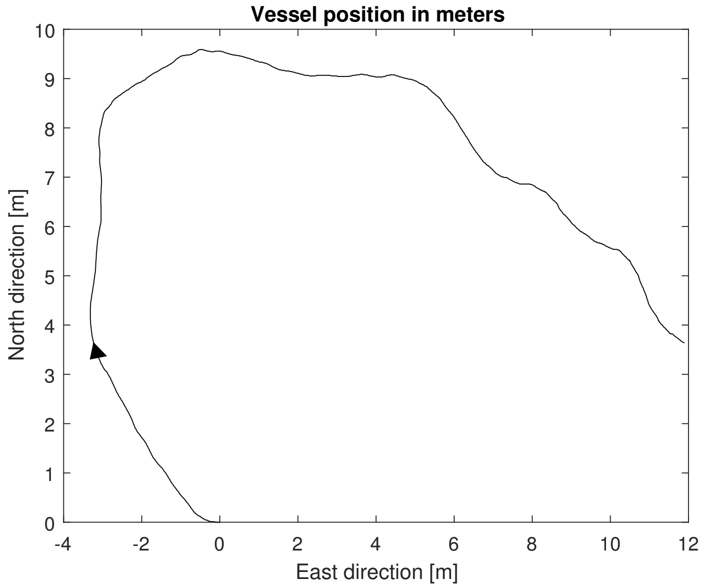

Figure 5.7. Vessel position in inertial coordinate system.

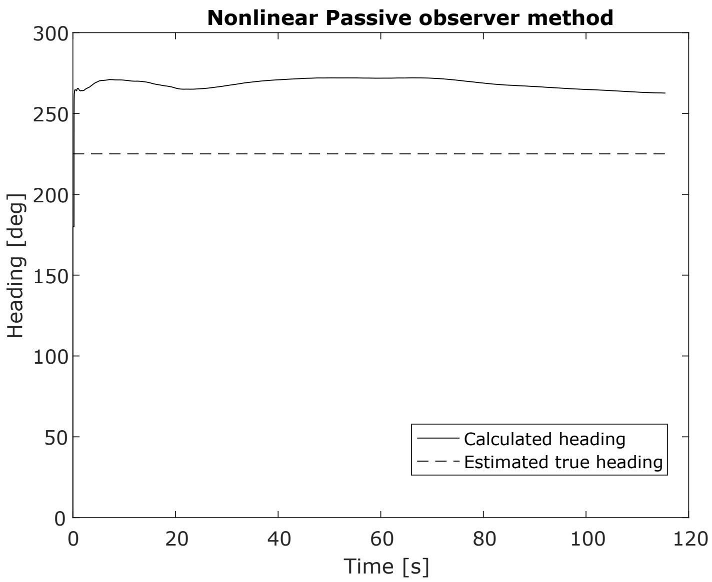

Figure 5.8. Estimated weather heading by the passive observer.

As seen in Figure 5.8 the passive observer method performed significantly worse in this case. The observer had difficulties determining the disturbance direction in the sway direction, which is more difficult than the surge direction since almost all disturbance is affecting surge.

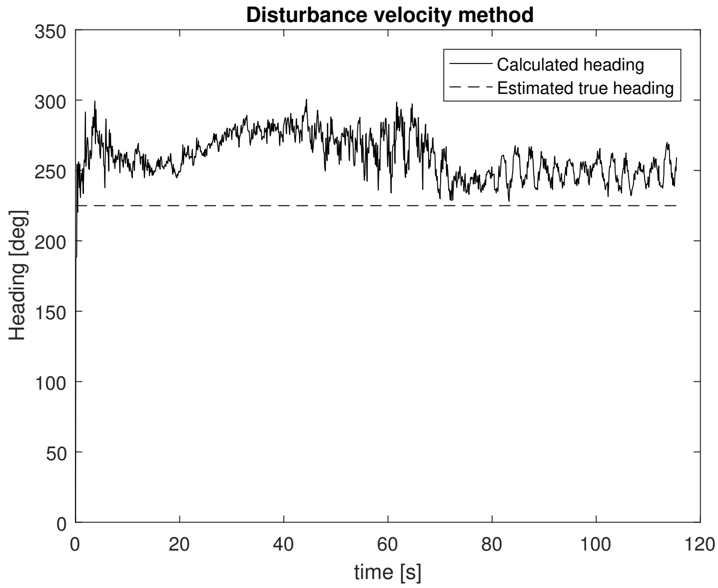

Figure 5.9. Estimated weather heading by the velocity based method.

Figure 5.9 shows the result of the second method. This result was also poorer than the previous case. It exhibits a constant overestimation of the weather force heading that arises due to an overestimation of the disturbance in the sway direction (see Appendix A for details of the data)

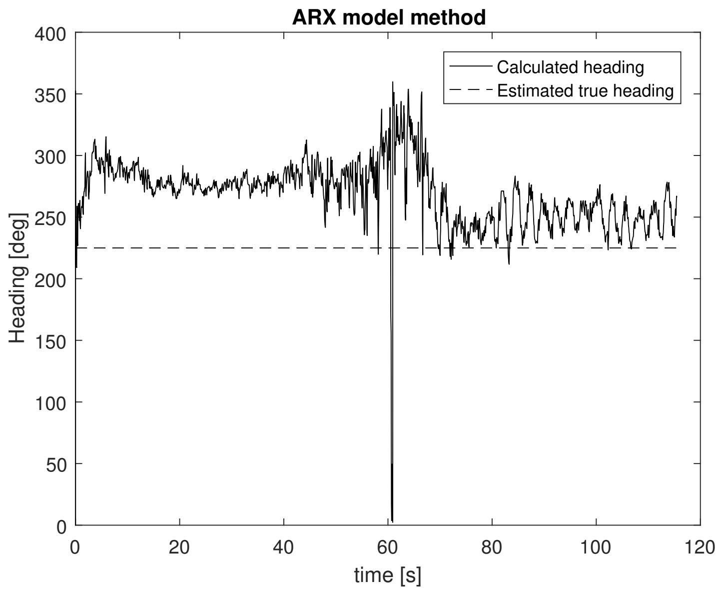

Figure 5.10. Estimated weather heading by the Arx model.

As in the previous test case, the Arx model performed at about the same level as the velocity estimation method but again at a slightly worse level as shown in Figure 5.10. This is likely due to the training data for the system identification failed to adequately capture the dynamics associated with the system inputs generated for this case.

5.4 Generality of the proposed solution

A question to examine is: Could the identified boat dynamics be used to solve the same problem for a different boat? To examine this a 50 feet boat was used with the same kind of actuator setup as the boat used in the previous sections. Another experiment was conducted with the same station keeping function active. The same model that was identified for the smaller boat was used to identify the weather heading. The purpose was to examine how general the dynamic model of the boat was.

Figure 5.11 shows the estimated weather heading based on the model of the smaller boat by using the disturbance velocity estimation method. The boat was facing away from the weather field. As can be seen, this was not possible at all. Similar results were found for the other two methods and when the boat was facing the weather. It should be noted that, though, that this experiment was performed at a different time when the weather forces where milder which can make it more difficult to estimate the weather heading.

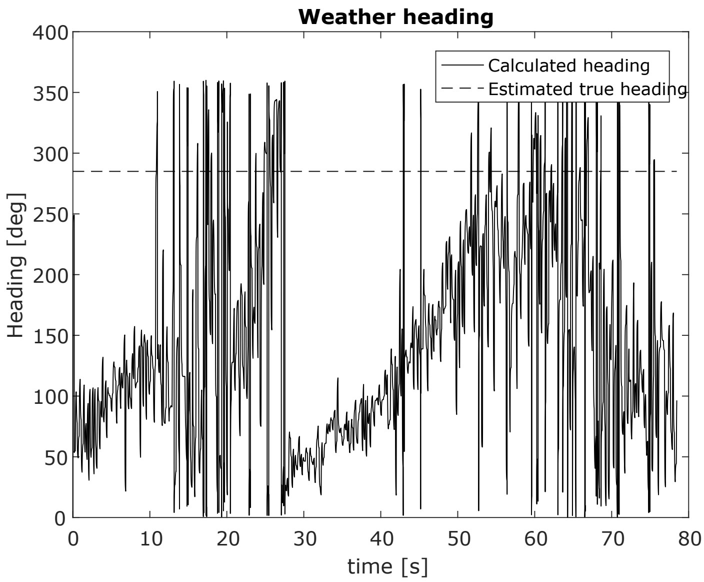

Figure 5.11. Identified model used on larger boat.

6 DISCUSSION

This chapter provides a discussion about the used methods, modelling aspects and future work.

The aim was to develop and implement new or extend current methods to automatically estimate the weather force heading. This was done by implementing and evaluating an existing method, the passive observer. One simplified method that estimates the weather velocity was developed and, finally, a well-known black box system identification method was used as well.

6.1 Methods

To summarize, the needed sea trials are: One acceleration in positive surge direction followed by constant speed. Then go in negative surge direction to capture the higher damping associated by driving a boat backwards, since boats are designed to go forwards normally. Next, travel with constant speed in either positive or negative sway, direction in order to capture the damping in that direction and estimate the reverse gear factor for low speed. If all steps are performed in sequence the time needed is just a couple of minutes.

The sea trials showed that it is crucial that low speed is maintained during data collection and when the speed is supposed to be constant that it actually is. Otherwise the parameter estimations will be poor. From a commercial point of view, it should be noted that the system identification manoeuvres should be used with care. If the data collected are poor, it might be better to use an educated guess such as the weight of the boat where it is known that the weight of a mid-size leisure boat varies between a couple of tones.

One advantage of the proposed methods is the elimination of the need for any rotational manoeuvres. With the nonlinear passive observer method, the weather heading estimation could be extended to include rotational movements, though this is not possible with the other two methods. Another manoeuvre is then needed, where rotational dynamics is introduced. This would most likely be operating the boat in a circle with an appropriate radius or a multitude of radii.

Another positive aspect of the proposed methods is that during deployment they are all passive in the sense that they do not have to interfere with performance of e.g. the control loop. The result could be used in a feed forward term but also just result in a number on screen telling the operator that turning a certain amount of degrees will improve station keeping performance.

As seen in Chapter 5 the time of convergence for the first experiment was quite fast, depending of which method was used, ranging from just a couple of seconds to about half a minute. However, for the second experiment the estimation was poorer. For the first method the accuracy was consistently about half of a quadrant. For the last two methods the error was also about half of a quadrant for the first minute of the experiment before the result converged to much better estimates (see Appendix A for an analysis of that result). The results suggest that the methods can quite fast reach an estimate but it might contain some error that gets corrected after a while due to the recursive estimation.

Because of currents the station keeping function deviates quite a bit from the chosen set point. How much the deviations could be reduced by introducing knowledge about the disturbances still needs to be researched. The proposed methods need to reduce the movements quite a bit before they could outperform the WOHC method, for instance.

The automatic control research on marine vessels focuses on industrial applications where these results would not be good enough for applications such as offshore drilling. For leisure activities on open sea it might be good enough. However, for the special cases in ports, for instance where movements are restricted, there is not enough data to show if the results are good enough.

Theoretically, for the case when the boat is facing the weather field it should be easy to estimate the disturbance in the direction the boat is facing and much harder in the direction that has little to no disturbance. However as seen in Appendix A this was not the case when the boat was facing the weather force field. This indicates that the model did not accurately captured the dynamics in that direction.

6.2 Modelling aspects

The Arx model was identified with disturbances present, it is impossible to have a perfect blank sea. It would be interesting to perform the data collection during various levels of disturbance to compare the performance.

During the data collection for the ARX system the input signals to the actuators was manually applied and might have suffered from issues such as too low resolution in the steps between rudder angles or input throttle. In this case two levels were used due to difficulty in manually control the input without reaching too high speeds. A more accurate way would be to program a routine that can cover a wider range of input signals with more accuracy. Arx models are linear and as shown in the theory chapter the dynamics are non-linear which means that perfect results cannot be expected.

By keeping the actuator model, but separating the rudder angles, a large non-linearity is removed from the system. This can be recommended because the rudder angles are well known and easy to separate from the rest of the dynamics.

7 CONCLUSION

The main research question, whether it is possible to estimate the weather heading without controlling a boat in a certain way or doing any measurements on the environment outside the boat, has been answered. It is possible to do such an estimation. Figure 7.1 shows the estimated resolution of the possible weather heading estimation.

It has been concluded that a solution that readily fits all boats does not seem likely to work. Before deciding which method to use, what resolution of the estimation is needed needs to be decided, such that an appropriate model can be identified.

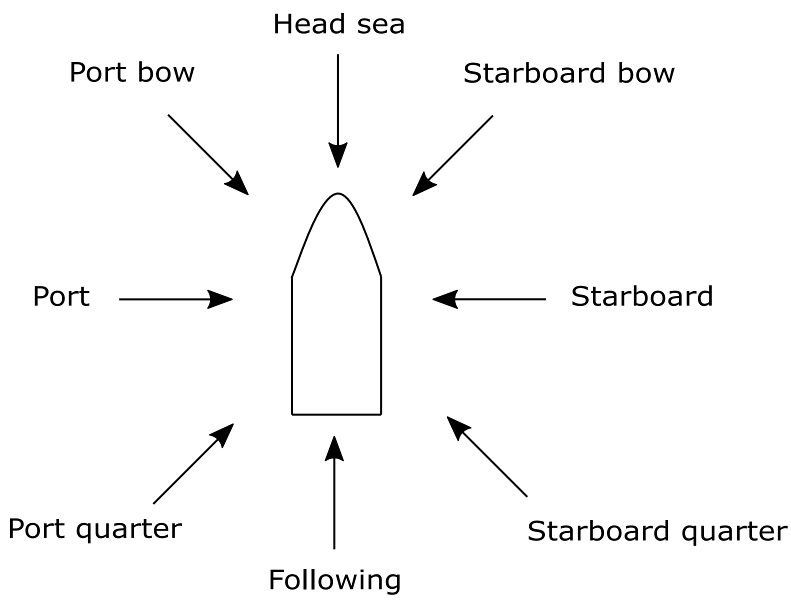

Figure 7.1. Estimated resolution of possible weather heading estimation.

Before deciding to implement the evaluated methods for estimating weather heading, the methods that rotates the boat into the optimal heading should be evaluated as the cases where they are unsuitable are special cases that might not happen commonly.

Yet another implication of the results is that it could be possible to develop a more advanced trajectory planing in autopilots that takes disturbances into consideration when planning a route.

7.1 Future work

When the weather heading is estimated to a satisfactory degree it can be integrated as a feed-forward term in the regulator doing station keeping. How much this improves the actual performance of the station keeping has not yet been evaluated.

Another possible advantage from the results is that it could be possible to develop a more advanced trajectory planning in autopilots that takes disturbances into consideration when planning the route. For instance, instead of going straight between two points and constantly having to compensate for disturbances, it might in some cases be beneficial to point the vessel into the disturbance field, so all disturbance is concentrated in the surge direction for as long as possible.

It would have been interesting to add sensors to measure the wind, waves and current. Not only to serve as a reference but also to allow more in-depth validation of the identified system by adding the disturbance force models to a simulation of the identified system to allow for better comparisons.

As shown, the system identification steps needs to be performed when disturbances are low. This is undesirable in commercial applications as it is difficult to schedule operations around the weather conditions. Hence it would be desirable to be able to do system identification at more difficult weather conditions. Attempts were made to filter out disturbances by detrending the states and input signals before the identification. However, these attempts failed to remove disturbances at a satisfactory level. More advanced methods are described for instance in (Shirdel *et al.* 2016).

It is not desirable to have the customer or installer of systems performing sea trials that are rather sensitive to the performance of the functionality. Another approach that has not been considered is the topic of machine learning. In Numakura *et al.* (2016) a method for modeling boat dynamics with the help of machine learning is described.

This could result in a method that could possibly bypass the issues of having to do trials to collect data for identification. Instead data could be continuously captured during dynamic positioning with different headings relative to the disturbance forces. The data could be detrended before applying it as training data for a neural network. This could result in a substitute model for the three discussed models that does not require any sea trials.

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Appendix A

Detailed results

This appendix provides a more in-depth analysis of possible causes for the worse performance when the vessel is pointing in the vicinity of the reverse heading of the weather forces. The discussion is focused on the disturbance velocity method due to its simple structure. There was an overestimation of the disturbance force heading, which means that either there was an underestimation of the surge velocity or an overestimation of the sway velocity. The data presented here is the same that was collected and used to estimate the weather heading as in Section 5.3.

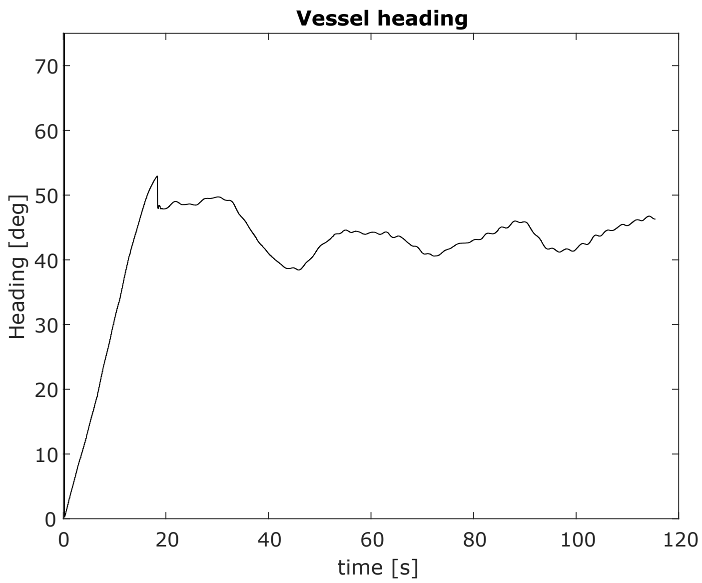

Figure A.1. Boat heading oscillates slightly.

As seen in Figure A.1, after the boats heading has been set to 50 degrees, the heading remains rather stable in relation to the movements in the surge and sway directions. This indicates that the Coriolis effect which has not been accounted for is low and are likely not the major cause of the error.

In Figure A.2 the inputs to the actuator function are shown, compared to the inputs for the other more successful case, they are similar.

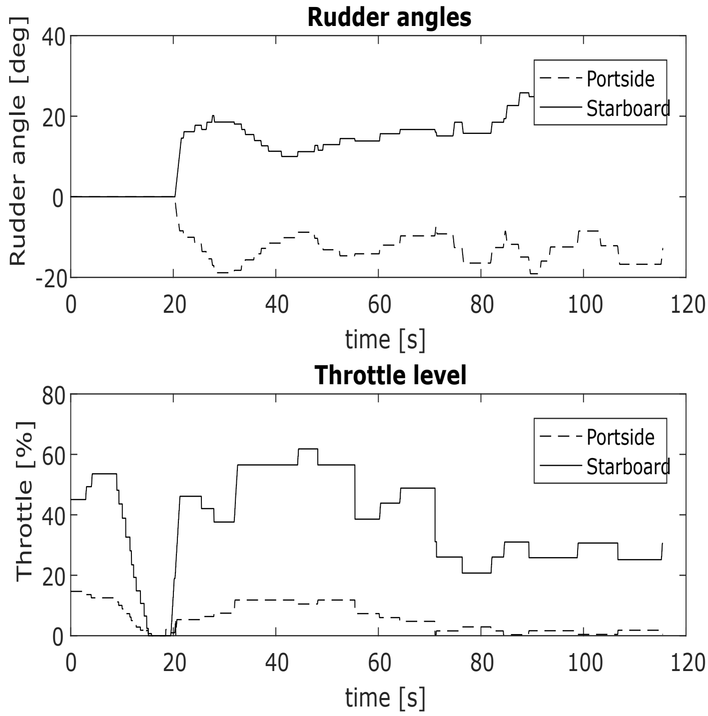

Figure A.2. Actuator inputs.

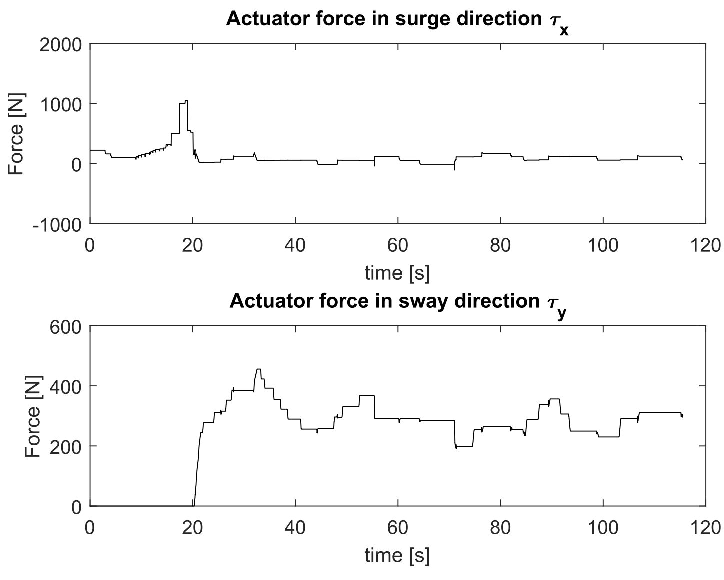

Figure A.3. Actuator forces.

In Figure A.3 the calculated actuator forces are shown. It can be noted that the force seems low for a dual 250 horsepower engine setup.

A possible explanation of the error is that the mass matrix was simplified to only the diagonal entries. In reality the mass is modeled as in the equation below. The Arx model was chosen as a 2 input and 2 output model to try to capture these off-diagonal elements. However, results did not improve, this might be explained by the fact that the rotational components were small and thus only the diagonal entries in Equation A.1 are non-zero.

$$\boldsymbol{M} = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mx_g - Y_{\dot{r}} \\ 0 & mx_g - Y_{\dot{r}} & I_z - N_{\dot{r}} \end{bmatrix} \tag{A.1}$$

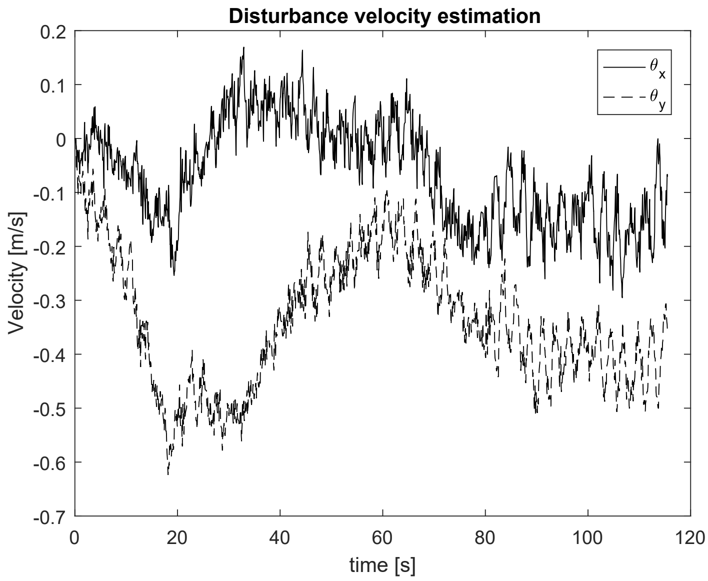

Figure A.4. Disturbance velocity estimation for facing the disturbance.

Ideal results would have shown Figure A.4 and Figure A.5 exactly the same. As seen in Figure 5.5 facing away from the disturbance force field yielded better results. By comparing the estimated disturbance velocity in Figure A.4 and Figure A.5 it can be seen that the major difference between the two figures is in Figure A.4, θ_x is positive during about half a minute of the experiment which would indicate that the weather forces are coming from the opposite direction then they actually are. This correlates with the worse estimation seen in Figure 5.9. This is due to an unbalance in the simulated model.

Either there is an underestimation of the actuator gain or an overestimation of the damping. However, as the method seems to be performing satisfying in the other test cases, it could be the case that there are un-modelled dynamics such as nonlinearities affecting the system. One such possibility is the reverse gear factor. During the experiment, the system placed the starboard engine in reverse except for a brief moment in the beginning. According to Carlton (2012) the reverse factor is not actually constant but depends on operating conditions. In Section 4.1.1 the reverse gear factor was identified as a constant. Results might improve if the reverse

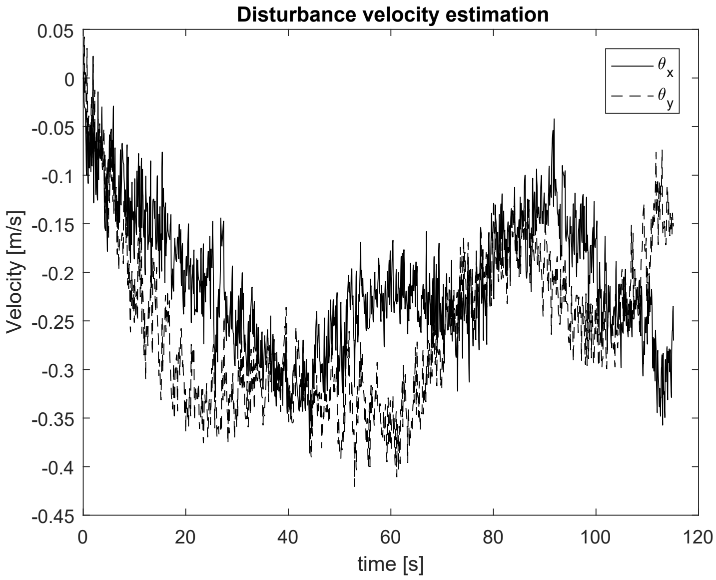

Figure A.5. Disturbance velocity estimation for facing away from the disturbance.

gear factor was identified during different operating conditions and stored in a look-up table.