Marine Control System I

Project Part 1

Report

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1 Introduction

In the course TMR4240 Marine Control Systems I, this report is an answer to the Project Part 1 in Marine Control Systems. By utilizing MATLAB and Simulink, a dynamic positioning system is going to be implemented for a vessel. In this task, 3 parts need to be designed: the current load, reference model and the controller.
The Vessel Dynamics block is given, the input of which is control force $\boldsymbol{\tau}$, and environmental force $\boldsymbol{\nu}_c$. The output of the block is the position and velocity of the vessel. The other blocks needs to be designed and modified. The design begins with the current loads and ends in the design of PID controller.

2 Process Plant Model

Aiming to design a DP control system, a mathematical model was derived to represent the motion and force. Based on the Newton' Second Law, we can get the nonlinear 6 DOF body-fixed coupled equation of low frequency motions as follows

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{C}_{RB}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{C}_A(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \mathbf{D}(\kappa, \boldsymbol{\nu}_r) + \mathbf{G}(\boldsymbol{\eta}) = \boldsymbol{\tau}_{env} + \boldsymbol{\tau}_{moor} + \boldsymbol{\tau}_{ice} + \boldsymbol{\tau}_{thr} \tag{2.1}$$

The terms on the left can be explained as:

- $\mathbf{M}\dot{\boldsymbol{\nu}}$ - General intertial forces
- $\mathbf{C}_{RB}(\boldsymbol{\nu})\boldsymbol{\nu}$ - Generalized Coriolis and centripetal forces on rigid body
- $\mathbf{C}_A(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r$ - Generalized Coriolis and centripetal forces on added mass
- $\mathbf{G}(\boldsymbol{\eta})$ - generalized restoring forces.

With the velocity vector relative to the effect of current loads is in Equation 2.2.

$$\boldsymbol{\nu}_r = \begin{bmatrix} u - u_c & v - v_c & w & p & q & r \end{bmatrix}^T \tag{2.2}$$

The forces one the right hand side are the generalized external forces. $\boldsymbol{\tau}_{env}$ are the low frequency environmental forces except current loads. $\boldsymbol{\tau}_{moor}$ are the forces from eventual mooring. $\boldsymbol{\tau}_{ice}$ represent loads from level ice, ice floes and ice ridges. $\boldsymbol{\tau}_{thr}$ is the control force generated by the propulsion system. The effect of the current load is included on the left hand side, with the relative velocity vector. Wave loads are not included in the low frequency motion.

3 Control Plant Model

For the controller design, we can easily derive the mathematical control model from the simplification of the process plant model above

$$\begin{gathered} \dot{\boldsymbol{\eta}} = \mathbf{R}(\psi)\boldsymbol{\nu} \\ \mathbf{M}_i\dot{\boldsymbol{\nu}}_i + \mathbf{D}_i\boldsymbol{\nu}_i + \mathbf{R}^T(\psi)\mathbf{G}_i\boldsymbol{\eta}_i = \boldsymbol{\tau}_{currenti} + \boldsymbol{\tau}_{thri} \end{gathered} \tag{3.1}$$

where $i = 3$ describes the 3 DOF horizontal model of surge, sway and yaw. $\boldsymbol{\nu} = [u, v, r]^T$ is body-fixed velocity vector and $\boldsymbol{\eta} = [x, y, \psi]^T$ is earth-fixed position vector. The $\mathbf{M}$, $\mathbf{D}$ and $\mathbf{G}$ matrix are calculated by implementing the $\mathbf{H}$ matrix

$$\mathbf{H}_{3\times 6} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.2}$$

$$\mathbf{M}_3 = \mathbf{H}_{3\times6}\mathbf{M}\mathbf{H}_{i\times6}^T \tag{3.3}$$

$$\mathbf{D}_3 = \mathbf{H}_{3\times6}\mathbf{D}\mathbf{H}_{i\times6}^T \tag{3.4}$$

$$\mathbf{G}_3 = \mathbf{H}_{3\times6}\mathbf{G}\mathbf{H}_{i\times6}^T \tag{3.5}$$

The parameters of $\mathbf{M}$, $\mathbf{D}$ and $\mathbf{G}$ can be extracted through MATLAB. The result is $\mathbf{D} = \mathbf{0}_{3\times3}$ and $\mathbf{G} = \mathbf{0}_{3\times3}$ since the vessel only has horizontal model under current loads and is not moored, which means the influence of damping and restoring is negligible.

$$\mathbf{M_3} = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mx_G - Y_{\dot{r}} \\ 0 & mx_G - N_{\dot{v}} & I_z - N_{\dot{r}} \end{bmatrix} \tag{3.6}$$

$$\mathbf{D_3} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{3.7}$$

$$\mathbf{G_3} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{3.8}$$

The corresponding linear LF state-space model can be formulated as

$$\begin{aligned} \dot{\mathbf{x}}_i &= \mathbf{A}_i\mathbf{x}_i + \mathbf{B}_i\boldsymbol{\tau}_{thr} + \mathbf{E}\boldsymbol{\nu_c} \\ \mathbf{y}_i &= \mathbf{C}_i\mathbf{x}_i + \mathbf{v}_i \end{aligned} \tag{3.9}$$

For $i = 3$, the state-space vector is $\mathbf{x}_3 = [u, v, r, x, y, \psi]^T$. The system matrix $\mathbf{A}_i$, control input matrix $\mathbf{B}_i$ and LF measurement matrix $\mathbf{C}_i$ are

$$\mathbf{A}_3 = \begin{bmatrix} -\mathbf{M}_3^{-1}\mathbf{D}_3 & -\mathbf{M}_3^{-1}\mathbf{G}_3 \\ \mathbf{I}_{3\times3} & \mathbf{0}_{3\times3} \end{bmatrix} \tag{3.10}$$

$$\mathbf{B}_3 = \begin{bmatrix} \mathbf{M}_3^{-1}\mathbf{H}_{3\times3} \\ \mathbf{0}_{3\times3}\mathbf{H}_{3\times3} \end{bmatrix} \tag{3.11}$$

$$\mathbf{C}_3 = 1 \tag{3.12}$$

The $\boldsymbol{C}$ matrix is equal to one since both the velocity and the position is measured.

The current velocity vector $\boldsymbol{\nu}_c$ is

$$\boldsymbol{\nu}_c = [V_c cos(\psi_c), V_c sin(\psi_c), 0]^T \tag{3.13}$$

The amplitude of current is V_c and the current direction is ψ_c. Since the vessel is in the surface, only the surface current is included. for simplicity, the variations in the current is neglected. The extra zeros in the model, is to get correct dimensions.

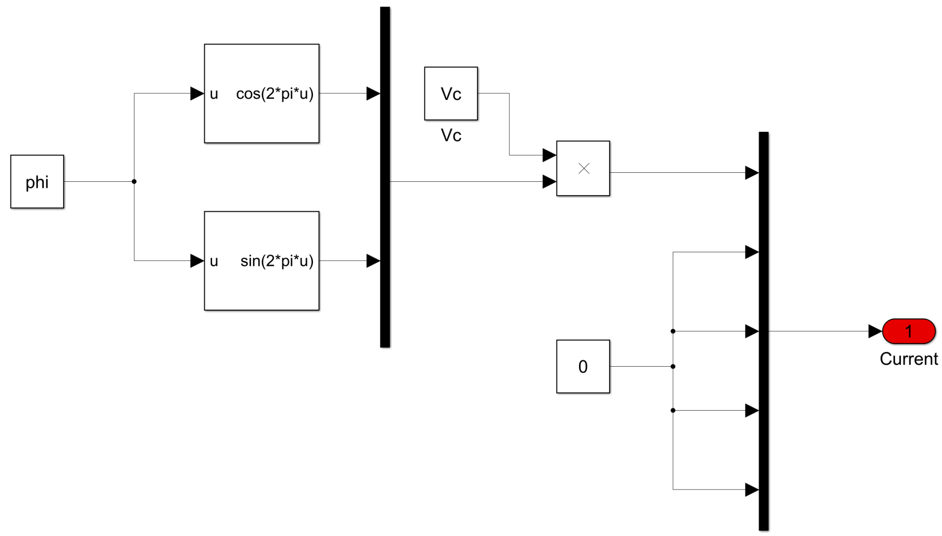


Figure 1: Block diagram of current load

The control force τ_{thr} is calculated from PID controller in Section 5.

4 Reference Model

In order to track a moving set point, and get a smooth transition, a reference model will need to be implemented for the DP control system. Since it is important with a smooth transition for both the position and velocity, while the acceleration can be on or off, the reference model will need to have order 2. Based on the earth-fixed frame, the automatic guidance function is

$$\mathbf{a}_d^e + \mathbf{\Omega}\mathbf{v}_d^e + \mathbf{\Gamma}\mathbf{x}_d^e = \mathbf{\Gamma}\mathbf{x}_{ref} \tag{4.1}$$

where η_r is our desired position. And the design parameters $\mathbf{\Omega}$ and $\mathbf{\Gamma}$ are all non-negative diagonal matrix representing damping and stiffness.

$$\begin{aligned} \mathbf{\Gamma} &= diag\{\omega_i^2\} \\ \mathbf{\Omega} &= diag\{2\xi_i\omega_i\} \end{aligned} \tag{4.2}$$

This was the starting point of tuning the reference model, and it was tuned until the output gave the set point. That critical damping is assumed, may make the model a bit slower, but overshoot will be prevented. For the natural periods, they will probably be somewhere between 70 and 200 seconds for surge, sway and yaw. For simplicity the natural period is set as the same as the period for the controller. This would in reality cause resonance, but since it is only a starting point for tuning the reference model, it can be used.

$$\begin{aligned} \mathbf{a}_d &= \mathbf{R}^T(\psi_d)\mathbf{a}_d^e \\ \mathbf{v}_d &= \mathbf{R}^T(\psi_d)\mathbf{v}_d^e \\ \mathbf{x}_d &= \mathbf{R}^T(\psi_d)\mathbf{x}_d^e \end{aligned} \tag{4.3}$$

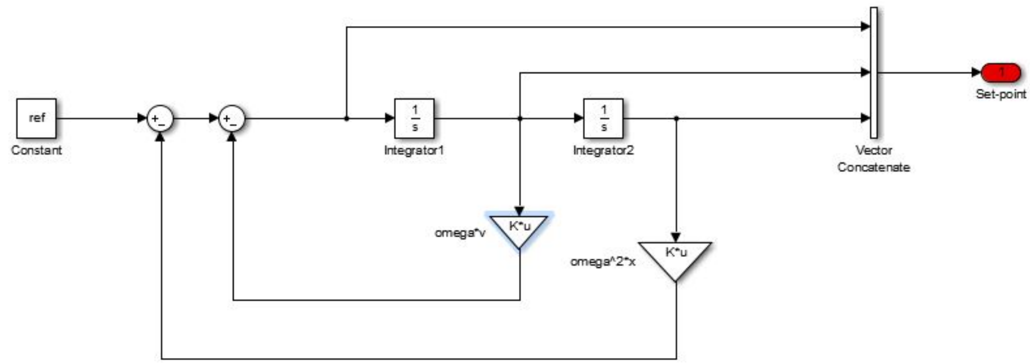


Figure 2: Block diagram of reference model

5 Controller Design

This is the most important and crucial part of a DP control design. In this part, we use PID to control the system. In this part, we choose PID controller to control the system. But in order to get the right error between the vessel motion and our desired setpoint, we need first to transfer earth-fixed frame to body-fixed frame. The vessel motions in this project are surge, sway and yaw (horizontal). Rotate the yaw angle ψ about Z-axis such that the transfer matrix is

$$\mathbf{R}^T(\psi) = \begin{bmatrix} cos\psi & sin\psi & 0 \\ sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{5.1}$$

After implementing the transformation above, we get the body-fixed position and velocity of vessel and our reference model. Thus, we have the relevant error as the input of PID controller.

$$\tau = K_p e(t) + K_i \int_0^t e(t) + K_d \dot{e}(t) \tag{5.2}$$

The PID controller need to be tuned. In this case it was tuned in succession with the reference model. To get the right amplitude of the gains, the first iteration was given like this(Fossen, p.381-382),

$$\begin{aligned} \omega_n &= \frac{\omega_b}{\sqrt{1 - 2\zeta^2 + \sqrt{4\zeta^4 - 4\zeta^2 + 2}}} \\ K_p &= m\omega_n^2 \\ K_d &\approx 2\zeta\omega_n m \\ K_i &= \frac{\omega_n}{10} K_p \end{aligned} \tag{5.3}$$

where ω_b is the control bandwidth. In this case it is assumed to be 0,05, and the relative damping ratio ζ was set to 1, since critical damping is desired. From this point the proportional gain was changed to get quicker control. The damping was changed to minimize oscillations, and K_i was adjusted to handle the standard deviation in a reasonable amount of time.

This is how the PID controller was implemented:

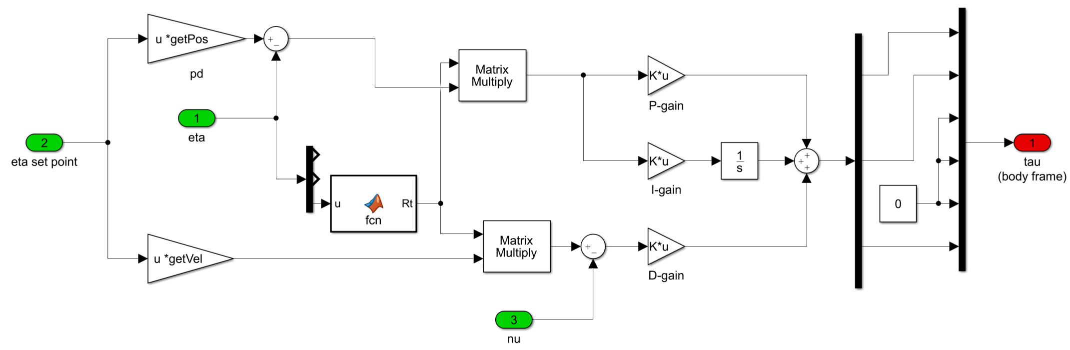


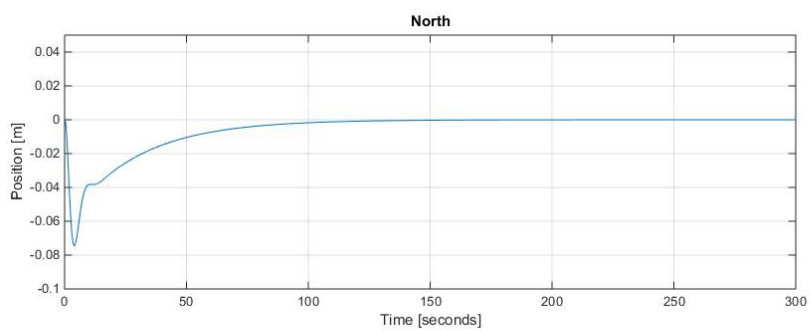
Figure 3: PID controller

The extra zeros in matrix before output, is to get the correct dimension. The MATLAB function block transforms the velocity from BODY-frame to NED-frame, and is there to use the current heading in the rotation matrix.

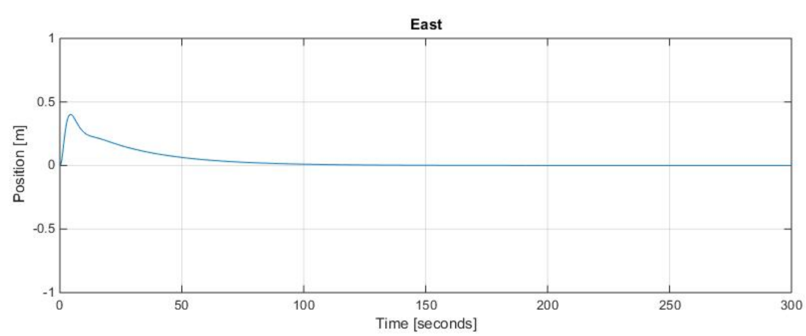
6 Simulations results

6.1 Simulation 1

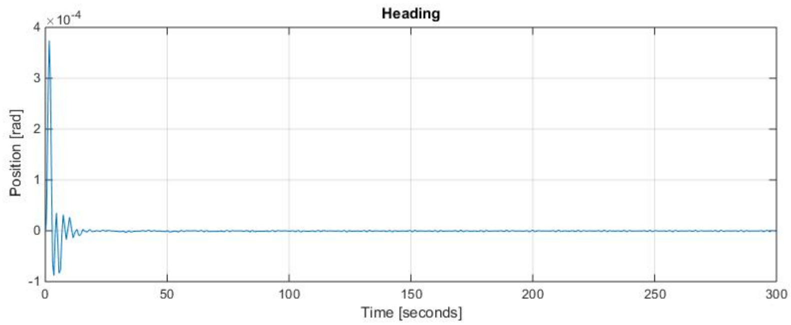
For the first simulation, the set point [0,0,0] and the current with 1 [m/s] going to southeast is set. The results show that the vessel moves to north with amplitude of about 0.075m and then returns back to the set point within 125s.



The change of position in surge is minimal. It starts to drift with the current at the beginning, before it retrieves the desired position.



The ship also drifts a bit with the current to the east. The drift here is larger than in surge, but still way under a meter.



The heading oscillates a bit around set point, but the oscillations are very small, and under 0.03 degrees. This must be seen as acceptable.

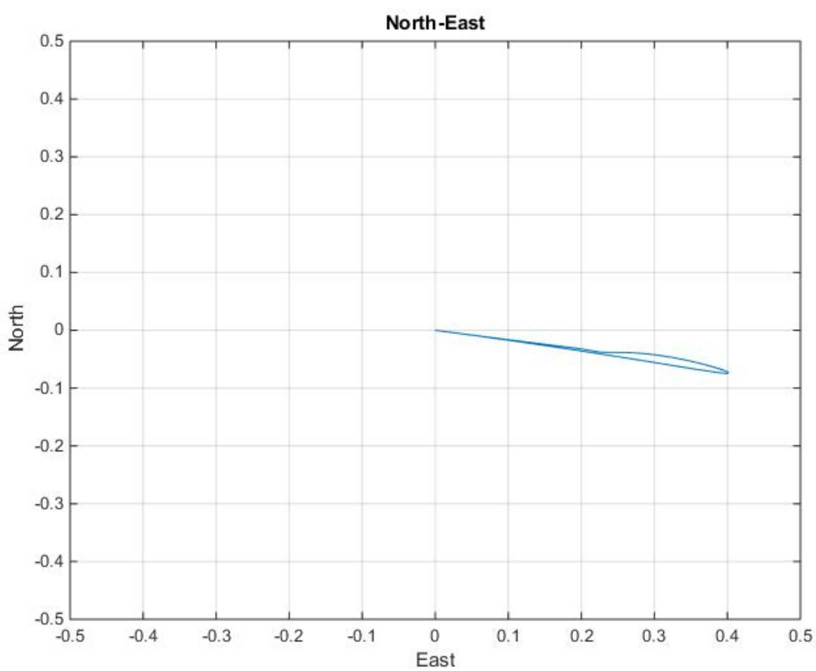
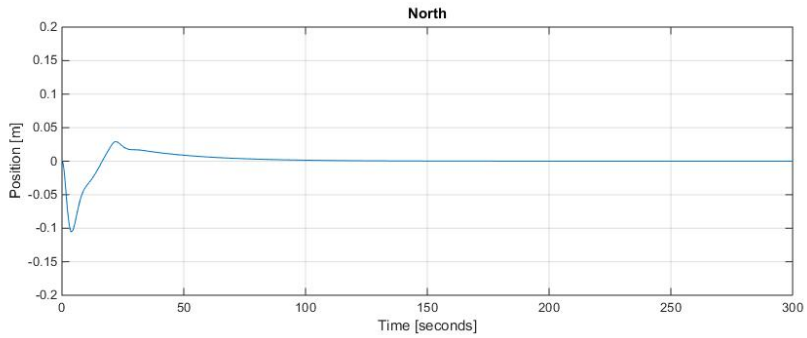


Figure 4: Trajectory

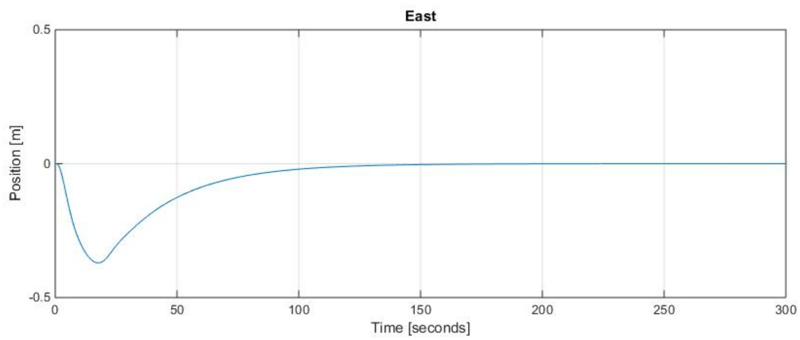
In the trajectory it is easy to see that the ship starts to drift with the current to South-East, before it get back to desired position.

6.2 Simulation 2

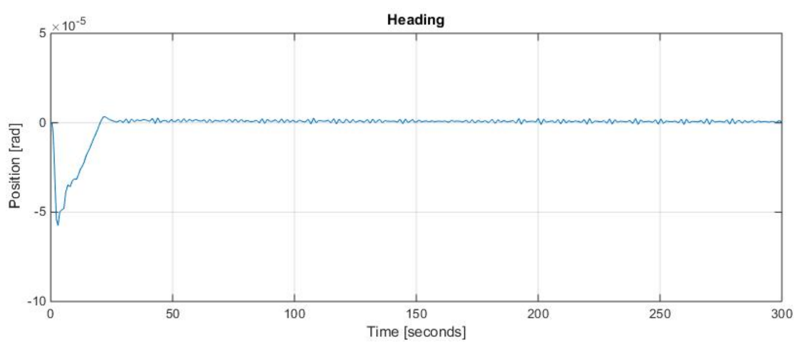
For the second simulation, the direction of current varies linearly coming from North to coming from East with the velocity of 1 [m/s] and the vessel set point is kept at the origin [0 0 0]. It takes 20 seconds for the current to shift between directions.



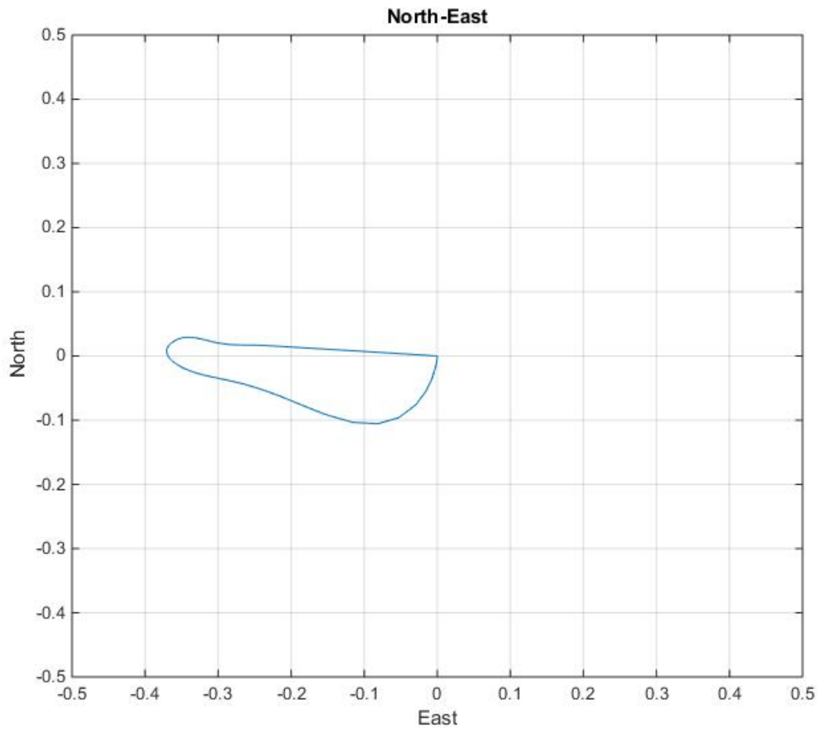
Since the current starts to the south, it is natural the the ship starts to drift in that direction. The drift is very small, and as the current shift it gets a small overshoot at it approaches set point. This is reasonable since the controller starts to counteract a current that shifts.



It starts to drift West as the current shift in this direction. The displacement is small, and it obtain set point within 150 seconds.



Again the heading oscillates a bit, but with very small angles. Since the heading oscillates at both stationary tasks, it may be a bit under-damped. This could probably have been improved with better tuning, starting with increasing the damping in yaw.



As seen above, the ship drifts more to the West than the South. This may be since the current velocity only being from the north at the beginning, while the current keeps its velocity to West til the end of simulation.

6.3 Simulation 3

From the third simulation task, the set point changes. The simulation results with and without a reference model are shown below.

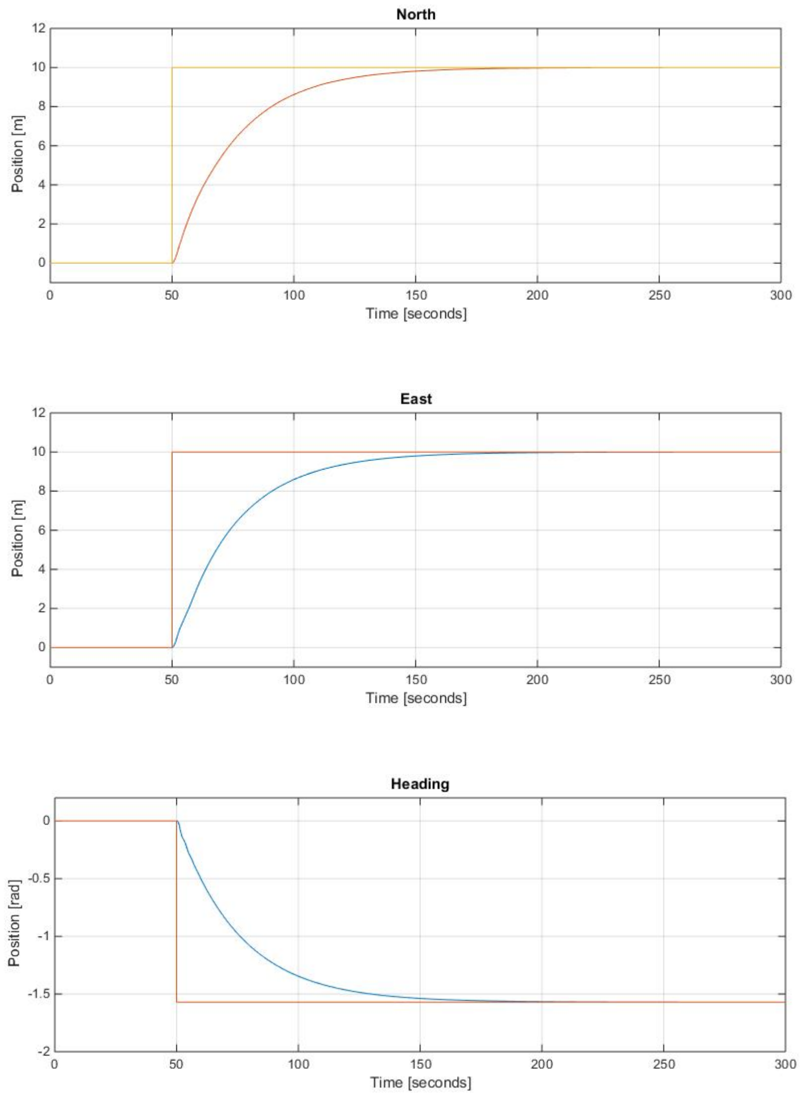


Figure 5: Plot of Position with reference model

With a reference model, the ship follows a smooth curve from initial position to set point. It is a bit slow, and could probably have been a bit more aggressive. Considering that it deviates under 2 meters after 50 seconds, it is still an acceptable model.

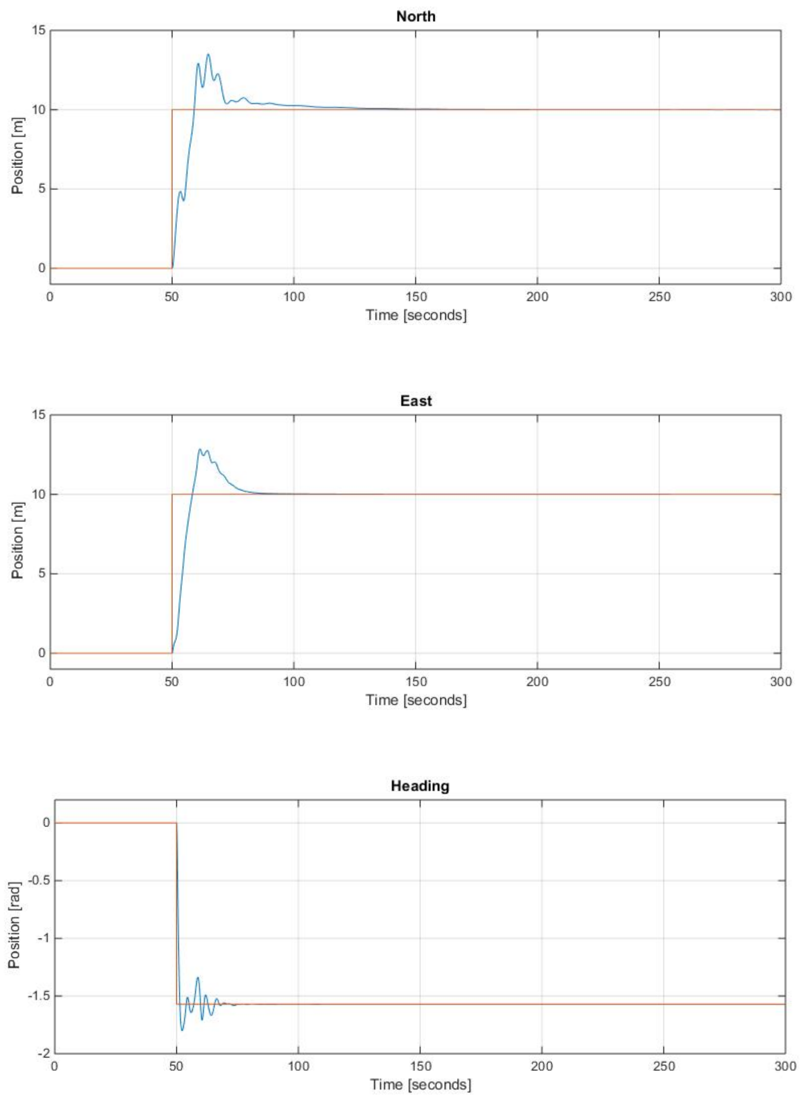


Figure 6: Plot of Position without reference model

The result without the reference model is oscillating a lot more, but does reach desired position. It does actually reach desired position much quicker than with the reference model. This is because the reference model works to change desired position slower than a discrete step. It has quite large overshoots comparing with the other plots. Taking into consideration that the system has been tuned with the reference model, this is not so bad.

6.4 Simulation 4

For the last test, the vessel follows 4 set points successively with heading changing once. The set points are [0 0 0] as the initial position then,[50 0 0] , [50 -50 0], [0 -50 -$\pi/2$], finishing at [0 0 -$\pi/2$].

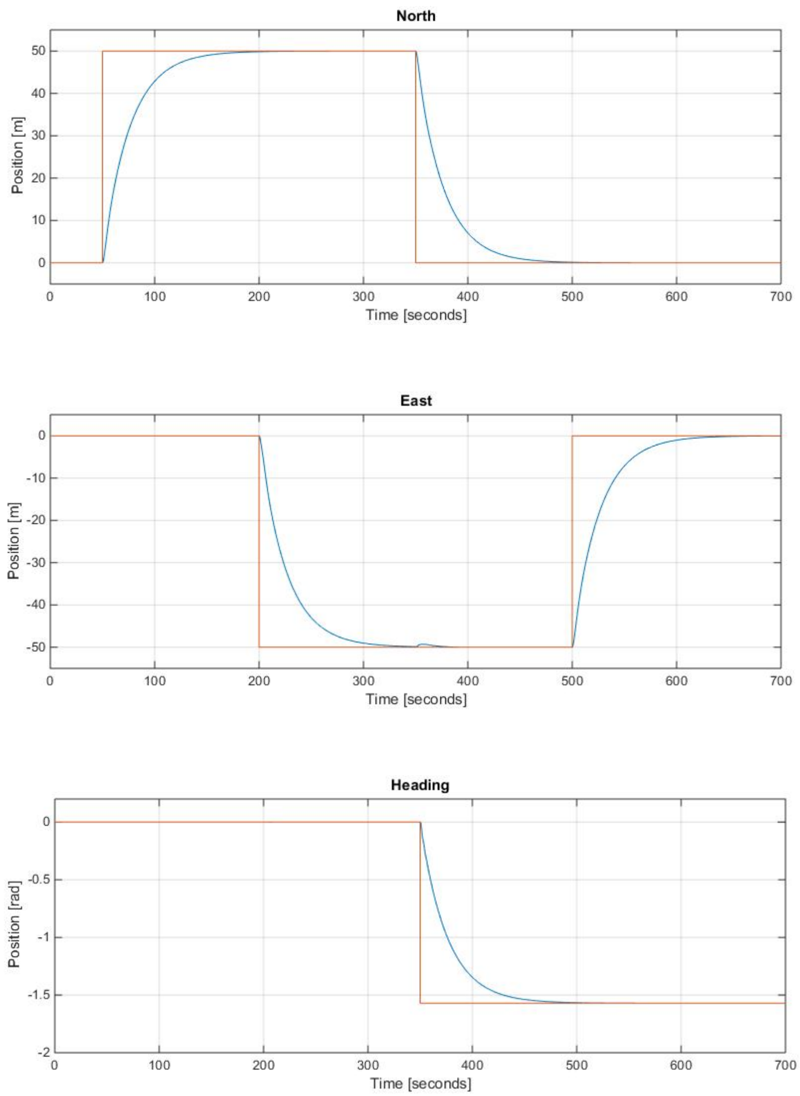


Figure 7: Plot of Position

It follows the desired path quite nicely. All the transitions are smooth, and within 700 seconds all the set points have been reached.

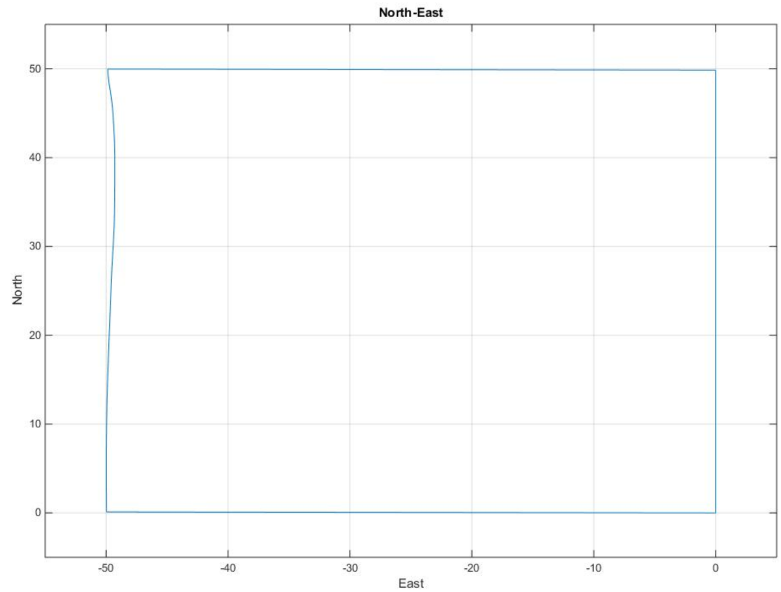


Figure 8: Trajectory

The result of trajectory shows that the ship manage to follow the set points perfectly with very slight deviation after the set-point η_2 because of the change of heading.

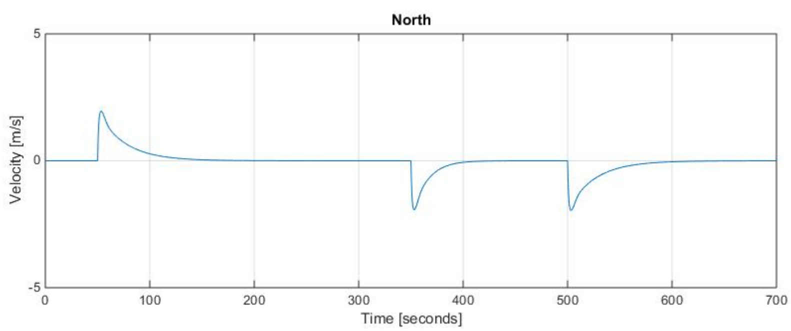


Figure 9: Plot of velocity of surge

The velocity in surge increases quickly and then reduces gradually based on the reference model. It is clear that there are 3 changes of velocity, the last of which is after the change of heading.

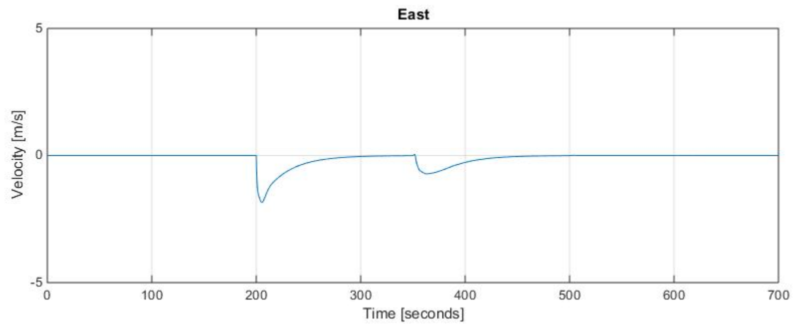


Figure 10: Plot of velocity of sway

In sway, velocity changes twice and the last one generated by heading changing is slower and smaller than the first one.

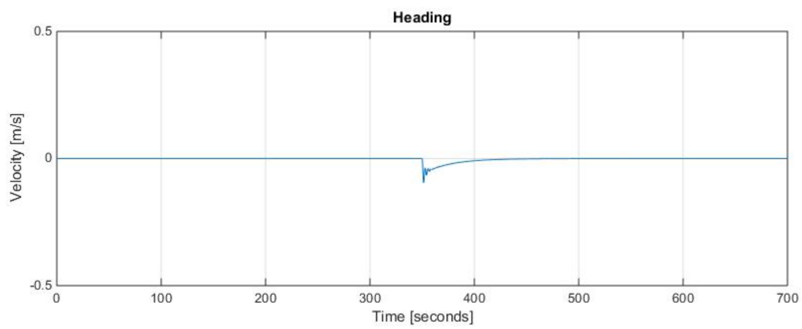


Figure 11: Plot of velocity of heading

The result shows that the velocity of heading starts to change at 350s with short oscillation and then reaches zero smoothly. Since the reference model has degree two, the output from the model is smooth. This must mean that there is something else making the velocity oscillate. It may have something to do with the heading being coupled to the sway motion, or that the ship can not control the heading directly.

References

[1] Asgeir J. Sørensen, *Marine Contorl System*. Department of Marine Technology, NTNU, 2013.

[2] Thor I. Fossen, *Handbook of Marine Craft Hydrodynamics and Motion Control*. John Wiley & Sons, 2011.