NTNU

TMR4240

Project - Part 1

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Contents

1 Introduction

In this part of project, a supply vessel simulator which simulates the vessel dynamics was given. Current load model, DP reference model and DP controller were yet to be designed and implemented. The DP reference model was introduced to filter the trajectories when ship moves towards a setpoint. The DP controller was designed so that the vessel has DP capabilities. It was desirable to make the vessel have good station-keeping and slow tracking capabilities.

After validation of those three models, five simulations were accomplished. The first two simulations were run to show the DP capability of the vessel, without and with varying current. The third simulation compares the tracking operation towards a setpoint with and without a reference model. After that, a path-following operation through several setpoints were tested to verify the reference model. In the end, an extra simulation were completed to find the optimal vessel heading by including a controller based on ZPC-W method.

Most of the results are satisfactory, while there are improvements to be done as well.

2 Current velocities

Current modelling is usually divided into two categories, which are surface current and full current profile. According to the lecture note, the former one is used in modelling of surface vessel response while the later one is used in modelling of risers, mooring lines, etc[3].

In this project assignment, the surface current velocities was implemented differently in the respective simulation tasks. In some the velocities was assumed constant, while in other it changed from e.g north to east. An example of how the current model was implemented can be seen in figure 1.

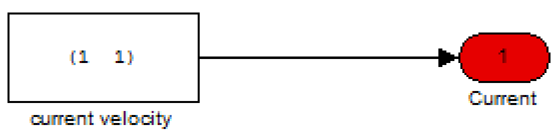

Figure 1: Example of current velocity block diagram

The first and second indexes in the current velocity vector are the current velocity decomposed in north and east direction respectively in the NED frame.

3 Controller

3.1 PID controller

The controller used for the vessel dynamic positioning was a PID controller on the following form:

$$\tau^b(1,2,6) = \begin{bmatrix} \tau_u \\ \tau_v \\ \tau_\psi \end{bmatrix} = R^T(\psi)\tau^n = R^T(\psi)(K_p(e) - K_d(\dot{\eta}) + K_i \int_0^\infty e(x)dx) \quad (1)$$

where $e = \eta_d - \eta$, $\dot{\eta} = R(\psi)\nu$ and $K_j = \begin{bmatrix} K_{ju} & 0 & 0 \\ 0 & K_{jv} & 0 \\ 0 & 0 & K_{jp} \end{bmatrix}$ with j = p,d,i respectively

In total (six degrees of freedom):

$$\tau^b = \begin{bmatrix} \tau_u \\ \tau_v \\ \tau_w \\ \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} \tau_u \\ \tau_v \\ 0 \\ 0 \\ 0 \\ \tau_\psi \end{bmatrix}$$

Here the assumption was that heave, roll and pitch (w,ϕ, θ) were already stabilized.

3.2 Controller gains

	Surge	Sway	Yaw
K_p	$2 \cdot 10^5$	$2 \cdot 10^5$	$8 \cdot 10^7$
K_d	$2 \cdot 10^6$	$2 \cdot 10^6$	$3 \cdot 10^9$
K_i	$3.5 \cdot 10^3$	$2 \cdot 10^3$	$1.25 \cdot 10^5$

<u>Were these values realistic?</u>
$\Rightarrow$ Yes. High numerical values on the controller gains were realistic due to that all units followed the SI, thus were τ_u and τ_v given in [N] while τ_ψ in [N·m]. The vessel had mass given of 6000 ton, without the added mass, and to have an actuator force moving that amount of mass high numerical values on the gains were needed.

3.3 Why a PID controller?

Due to the fact that a PID controller are intensively used in the industry thanks to their easy implementation, robustness and the fact that they get the job done, a PID controller was implemented.

The reason for why a PID was used, and not an PI or PD controller, was due to that both the integral and derivative terms of the controller was needed. In other words the stationary error of the system, $e_\infty = \eta_{d_\infty} - \eta_\infty$, required a very large proportional gain to tend to zero, if the integral term was not included. The system also needed damping, thus a PID controller.

3.4 How were the controller gains tuned?

To find the controller gains a trial and error approach was used. An Lyapunov function could also been used, but to find the correct function and prove stability for the system with it seemed unnecessary and inconvenient, as a trial and error approach could give a satisfactory behaviour.

As known an PID controller is easier to tune for a system where the states are not coupled. Here, a motion in sway would give a motion in yaw. To simplify this the PID controller was tuned in the NED frame instead of the body frame as it can be seen from equation (1). The reason for that is in NED-frame the axis are not dependent on the heading of the vessel. Thus, by station keeping the vessel at origin with only current in the surge direction a controller for surge was found. The same controller gains parameters yielded for sway, but were changed a little due to yaw. When tuning the yaw-controller a current in the North-East was given with a speed of of $\sqrt{2}$ [m/s].

The way the tuning was done was by first increasing the proportional gain until the graph showed some oscillations. Then a derivation (damping) gain was tuned to smooth out the curve. The integral term was tuned to remove the stationary difference that remained.

3.5 Simulink

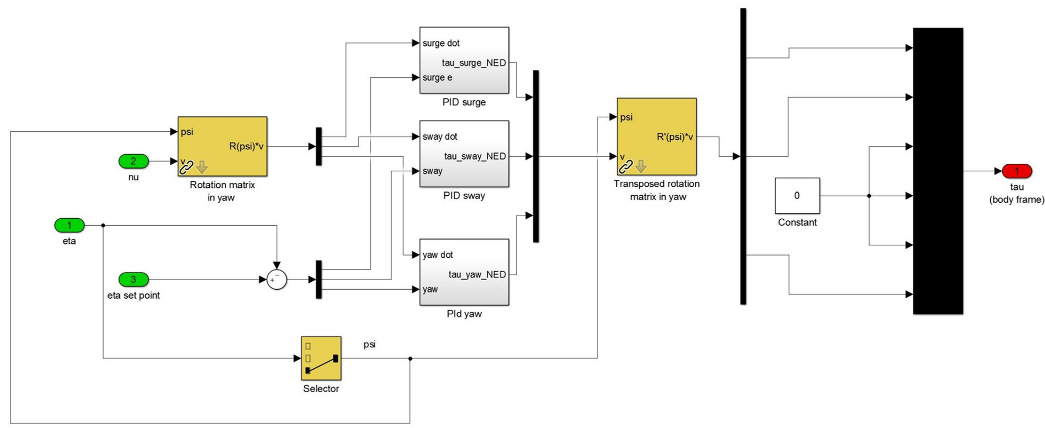

Figure 2: PID controller for DP control

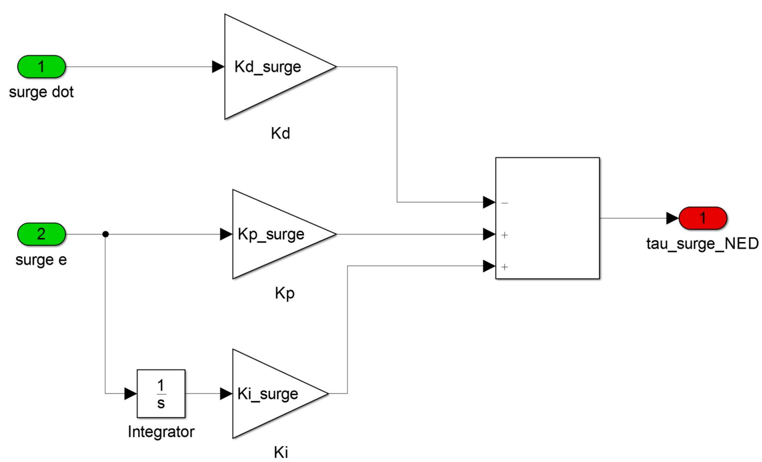

Figure 3: PID controller for surge

The same block diagram structure as shown in figure 3 yielded for sway and yaw.

4 Reference Model

4.1 First order Reference Model

A simple first order low-pass filter was implemented as reference model and it turned out to work well, see Section 5: Simulation, As the controller for the vessel consisted of the states surge, sway and yaw, the reference model was be applied individually by using transfer function to each state. Later, setpoint filters were to be tuned to make the actuators to work smoothly. The block diagram of the reference model is shown in figure 4.

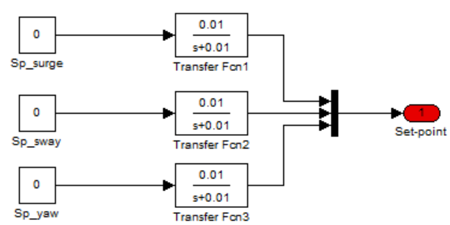

Figure 4: Reference model block diagram

4.2 How were the time constants found?

The different time constants were found by a trial and error approach. As the the simulation with the reference model were started, different values of the time constants were applied. The result with a smaller time constant resulted in an overshoot in the states affected, as the there was a coupling between surge and sway. A higher time constant resulted in a slow controller, the reference used more time to reach the desired setpoint.

4.3 Why use a reference model?

In tracking operations, where a ship moves from one position to another, a reference model must be introduced to achieve a smooth path following. Given a new desired setpoint, a reference model generates smooth reference trajectories for the vessel to follow. Optimal path planning and weathervaning are involved in a more advanced case.

In order to ensure that the state reference of a control system complies with the dynamical capabilities of the system, the commanded state can be passed through a low-pass filter. The filter, which is called a reference model, keeps the output from the control system within the physical capabilities of the actuators of the system.

A low-pass filtering reference model can for example be used in combination with PID control of the yaw motion of a vessel. Since the derivative part of the PID controller includes the derivative of the reference yaw angle with respect to time, any steps in the reference yaw angle would make the output from the PID controller very large. This very large control output is avoided by using a reference model to a low-pass filter the reference yaw angle.

5 Simulation

5.1 Simulation 1

The first simulation was to see how good the DP controller could keep the reference setpoint [0m 0m 0rad] when a current with speed 1 m/s was going southeast.

5.1.1 Simulink

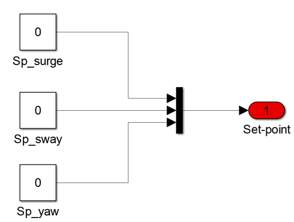

Figure 5: Simulink implementation of the reference model

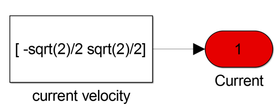

Figure 6: Simulink implementation of the current model

5.1.2 Plots

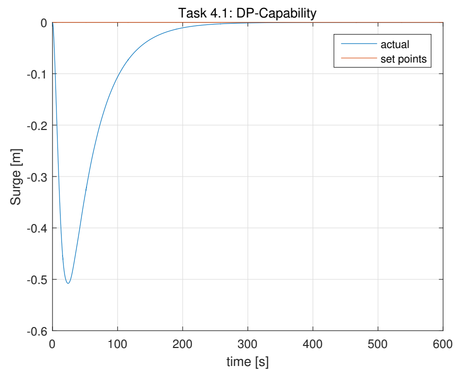

Figure 7: DP Capability: Surge

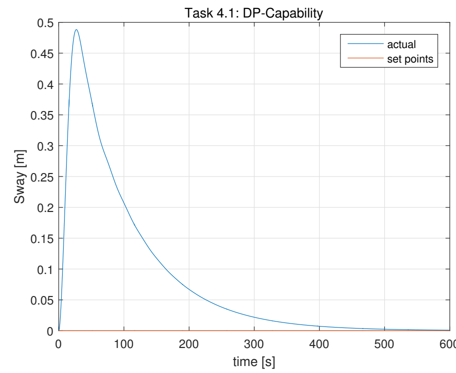

Figure 9: DP Capability: Sway

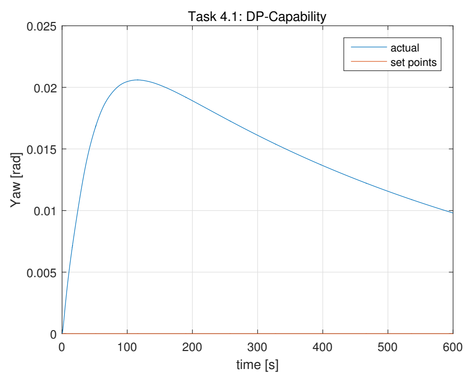

Figure 8: DP Capability (1 of 2): Yaw

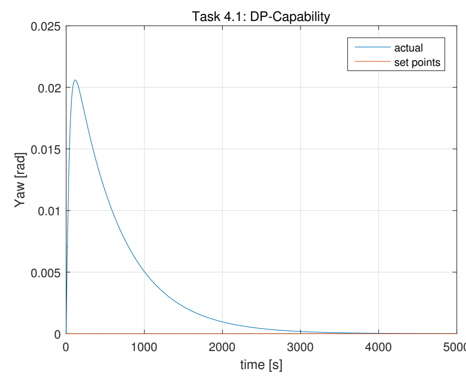

Figure 10: DP Capability (2 of 2): Yaw

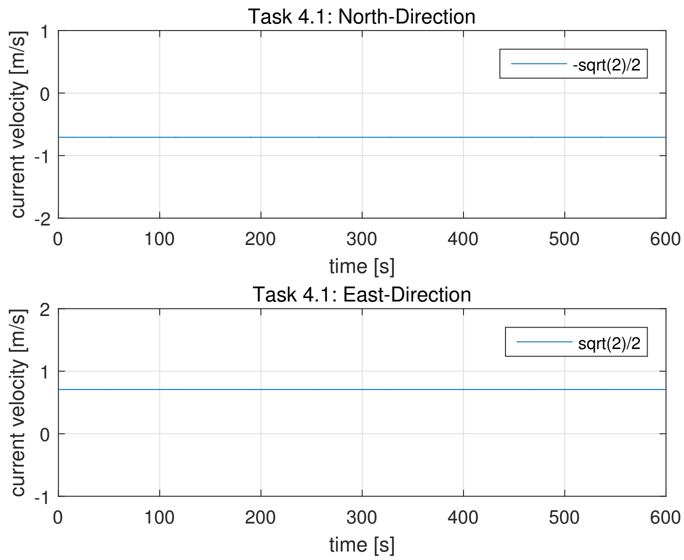

Figure 11: Southeast current with speed 1 m/s

5.1.3 Comments

The figures showed that with the given controller gains and the current, the vessel reached the reference. The sway reached the reference fastest at 200 seconds, while the yaw used a significant more time. One can argue for the controllers could have been tuned better, especially on yaw, but due to the coupling between sway and yaw and the fact that the deviations are quite small, the results seemed satisfactory. The reason for why sway was slower than surge was due to the coupling between sway and yaw.

5.2 Simulation 2

As simulation 1 the objective was to test the DP capability of the vessel. In this part the DP controller illustrated how well it would perform to keep the vessel at the original place while the current changed linearly from [1,0] to [0,1], north to east. The change from [1,0] to [0,1] happened in 200 seconds and saturation blocks were used on the current velocities to ensure that the velocity stayed within the limits.

5.2.1 Simulink

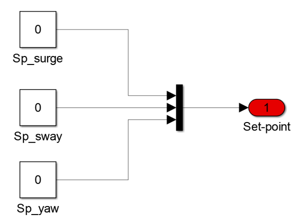

Figure 12: Simulink implementation of the reference model

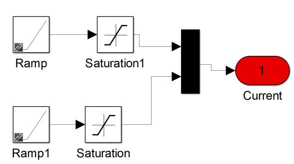

Figure 13: Simulink implementation of the current model

5.2.2 Plots

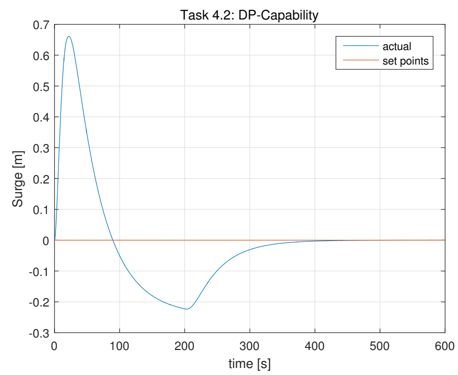

Figure 14: DP Capability: Surge

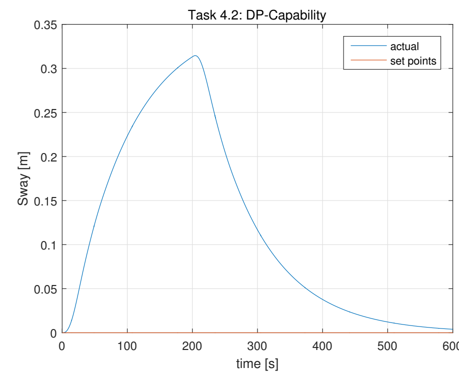

Figure 16: DP Capability: Sway

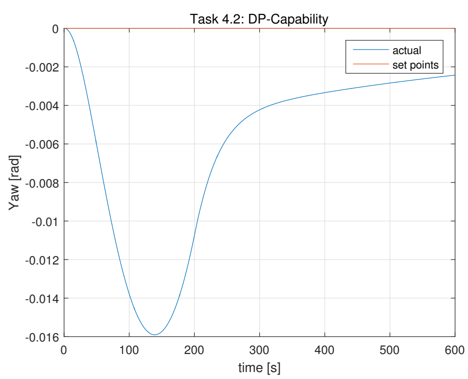

Figure 15: DP Capability: Yaw

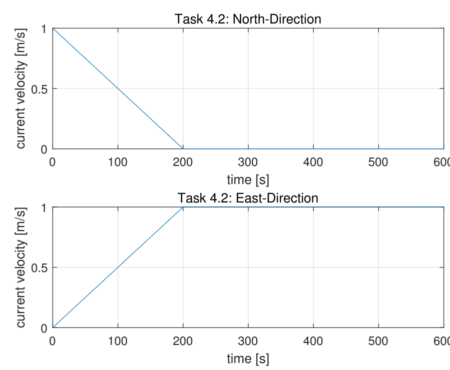

Figure 17: Northeast current

5.2.3 Comments

As in the previous simulation the figures 14∼16 showed that that the vessel reached the reference. However an overshoot in surge was observed, thus showing a slightly overdamping. This could have been fixed by reducing the integral controller gain, namely K_i, such that a critical response was obtained. However the overshoot is not that large, ≈ 0.22 rad (12.6deg). The surge and yaw were slower than the surge controller, which was expected due to the comments in previous simulation. Figure 17 shows the current change from north to east.

5.3 Simulation 3

In this simulation the vessel was supposed to go from an initial position to another position, with and without using the reference model. Due to the task did not specify any current the current was set to zero.

The desired position was set to [10m 10m $\frac{3\pi}{2}$rad] in the reference model, and due to a low time constant, 20 seconds, the states got overshoot. This was fixed by increasing time constant to 100 seconds in low pass filters until a smooth path for the initial position to the desired setpoint was obtained.

The simulation without the reference model was done by removing the the low pass filters from the reference model and send the desired setpoint straight to the controller. A significant overshoot could be seen. The reason for the overshoot is the large difference between the initial setpoint given to the controller and the initial actual position of the vessel. The large difference leads to a large control input to the vessel, giving the vessel a too high speed to stop at the desired setpoint.

5.3.1 Simulink

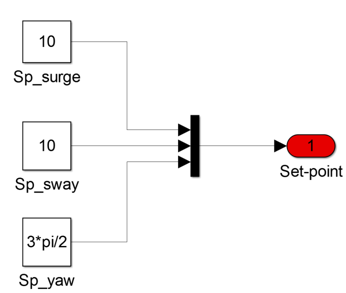

Figure 18: Simulink implementation of the reference model

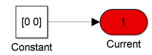

Figure 19: Simulink implementation of the current model

5.3.2 Plots

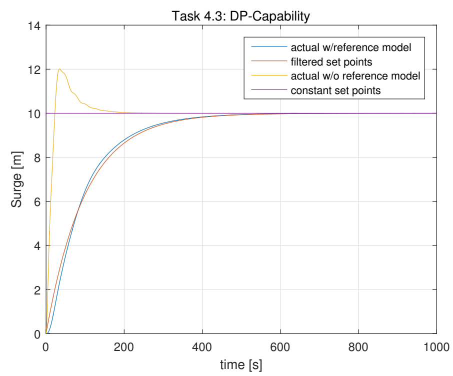

Figure 20: DP Capability: Surge

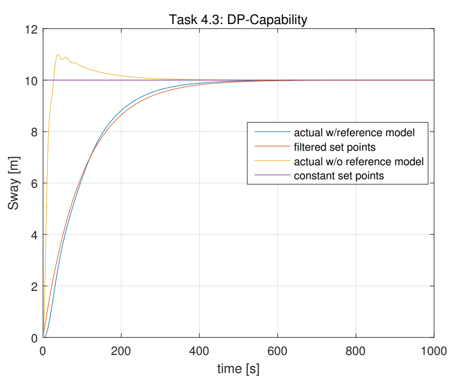

Figure 21: DP Capability: Sway

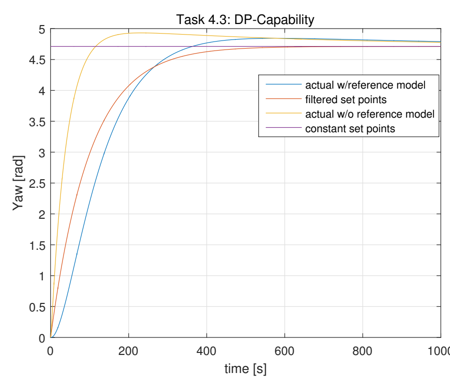

Figure 22: DP Capability: Yaw

5.3.3 Comments

Here it was seen that surge and sway behaved as expected when they were modeled with and without the the reference model. The figures 20∼21 showed that with the reference model the trajectories of the vessel were smooth and critically damped, and without the reference model the trajectories were faster and overdamped. For DP vessels a huge motion is undesired and the figures showed how the reference model influence the controller in making a more smooth and less aggressive response as a thrust. One can argue that in figure 20 the vessel moves 12 m in $\approx$ 50 seconds and that would be acceptable, but the objective here were to see the importance of using a reference model and the time delay and damping it induces to the system. The reference model had the same affect on the yaw and in figure 22 it can be seen that the slope is higher without the reference model than with. However the time constant in the yaw could have been chosen to be larger since the vessel passed the reference before getting to it.

5.4 Simulation 4

The last simulation was to simulate the vessel going through a series of setpoints. To implement this several step functions were placed in the reference model and summed up to give the desired course. In this way the setpoints were changed at given times as what is indicated in Figure 25, 26 and 27. The times were chosen such that the vessel had enough time to reach each setpoint position. Also in this simulation there were not specified any current, hence the current was assumed zero.

5.4.1 Simulink

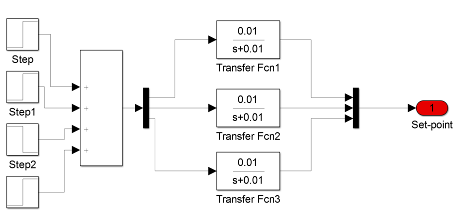

Figure 23: Simulink implementation of the reference model

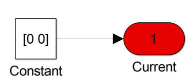

Figure 24: Simulink implementation of the current model

5.4.2 Plots

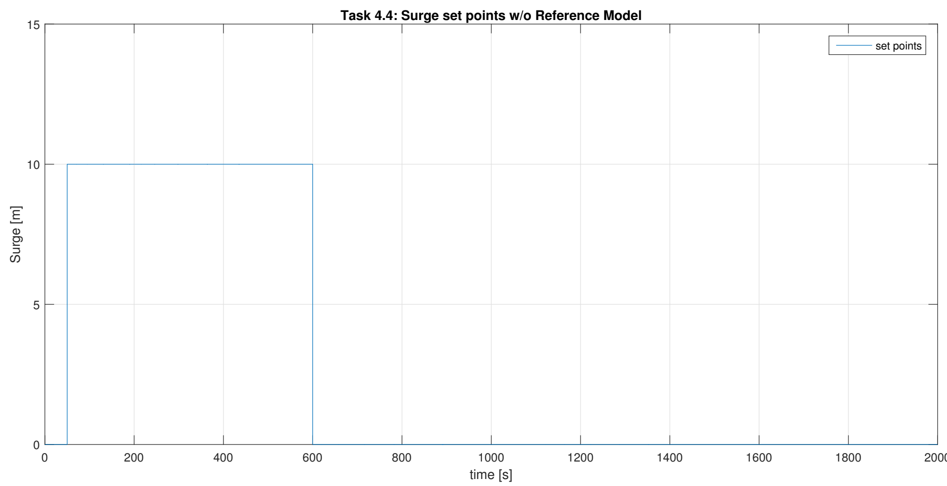

Figure 25: Unfiltered setpoints: Surge

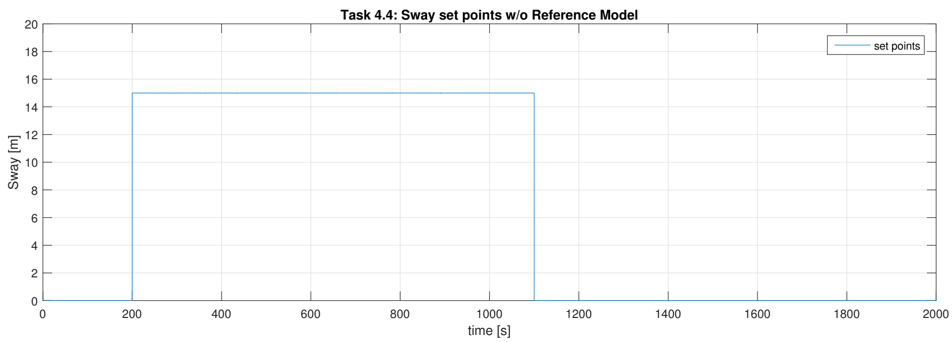

Figure 26: Unfiltered setpoints: Sway

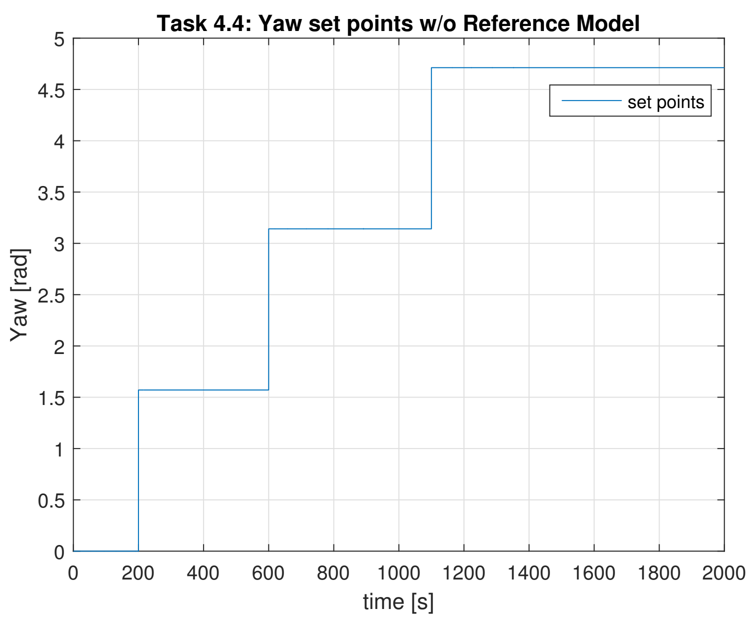

Figure 27: Unfiltered setpoints: Yaw

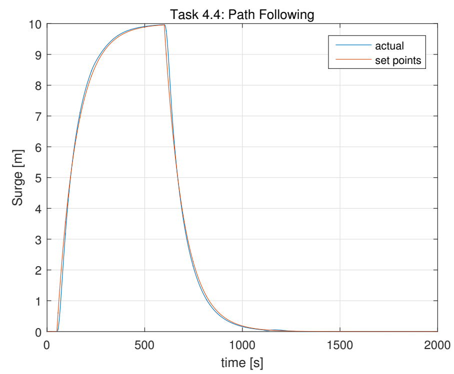

Figure 28: Path following: Surge

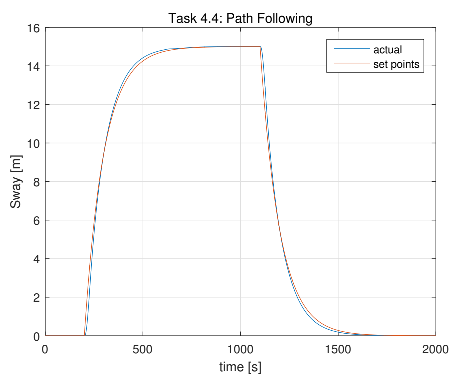

Figure 29: Path following: Sway

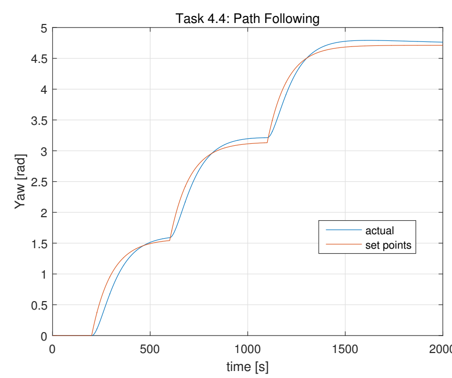

Figure 30: Path following: Yaw

5.4.3 Comments

It can be seen in figure 28, 29 and 30 that the surge and sway followed the path nicely compared to yaw which had some difficulties. The timestep was varying and was chosen such that the vessel had enough time to reach the set point before a new setpoint was given. Thus the timestep were chosen on intuition by looking at how far the new point was from the previous point for the respective state. That the yaw controller had problems with reaching the desired can be fixed by either having a longer time constant in the reference model or by modifying the yaw controller.

5.5 Extra Simulation

Finding the optimal heading angle (weathervaning) is an important part of vessel DP capabilities, especially for vessels with turret mooring system. In this simulation, a controller is implemented to position the vessel at a favorable angle towards current by using ZPC-W (Zero Power Control-Weathervane) method developed by Michel Miyazaki and Eduardo Tannuri[2].

The idea of ZPC-W is to implement a zero sway force controller so that the final vessel heading during dynamic positioning is the one that produces zero resultant sway force[1]. The proposed adaption law of the heading setpoint is indicated in [1] as:

$$\dot{\Psi}_{SP} = K \cdot F^{y}_{DP} \tag{2}$$

where $\dot{\Psi}_{SP}$ is the vessel heading setpoint time-derivative and K is the adaptation gain. While the integral of $\dot{\Psi}_{SP}$ gives the updated heading setpoint. The block diagram of the controller is presented in Figure 31 the following subsection.

5.5.1 Simulink

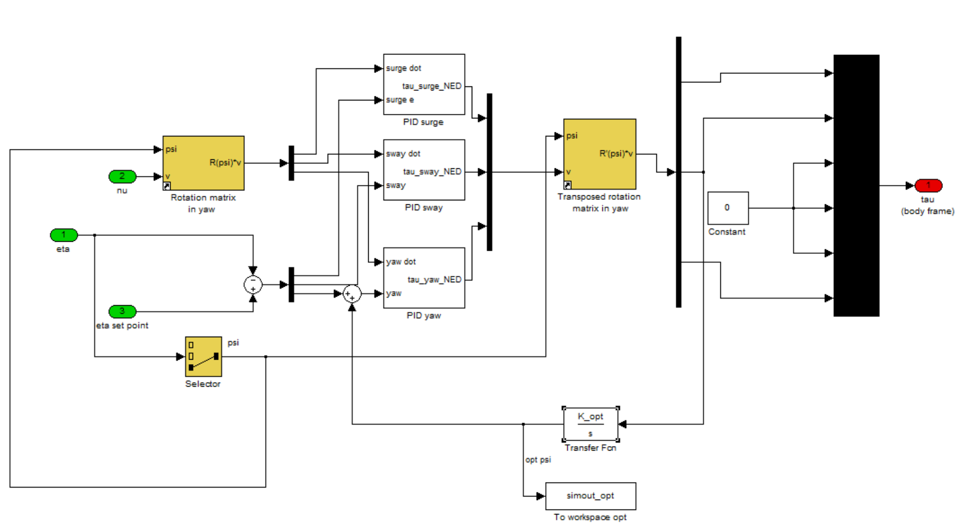

Figure 31: Simulink implementation of the ZPC-W controller

5.5.2 Plots

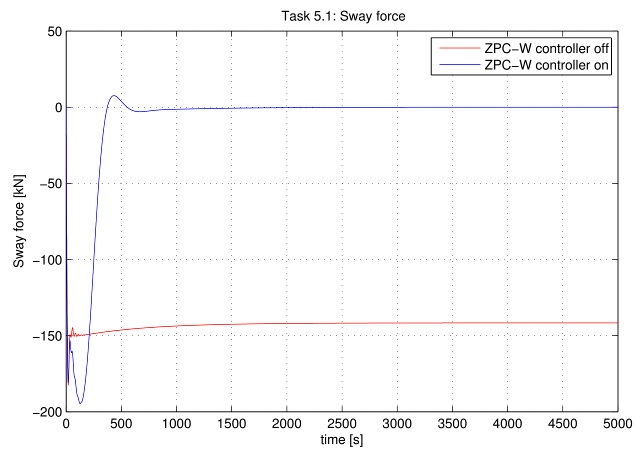

Figure 32: Sway forces with and without ZPC-W controller

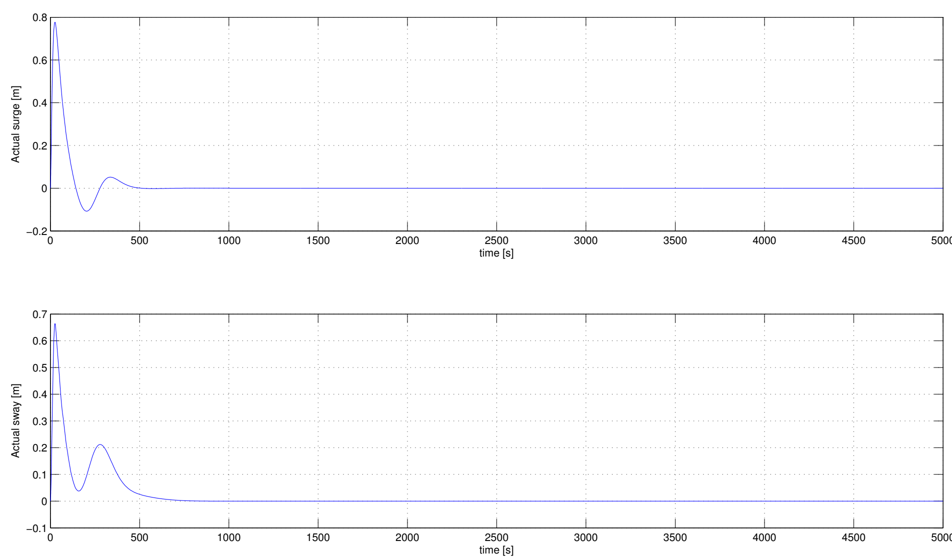

Figure 33: Surge and sway with ZPC-W controller turned on

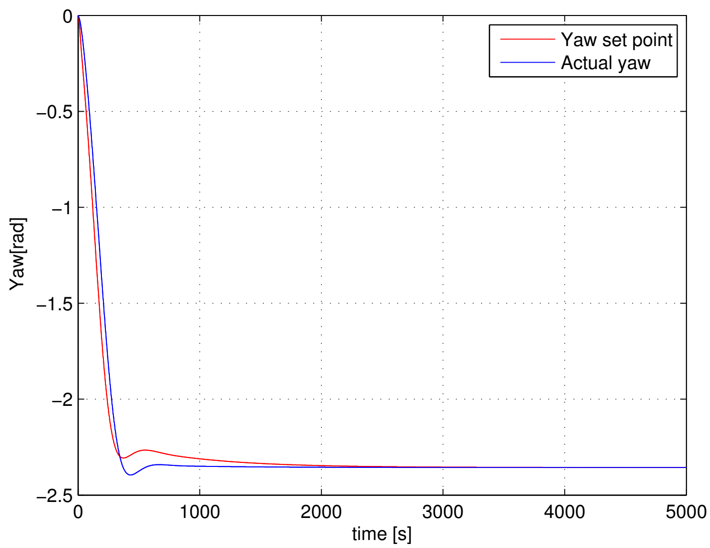

Figure 34: Yaw angle with ZPC-W controller turned on

5.5.3 Comments

In this simulation case, the setpoint is originally defined as [0m 0m 0rad], and the current is going to north-east. Adaptation gain is set to 5×10^{-8}.

When the ZPC-W is not turned on, the DP sway force is -140 kN, as shown in figure 32. After the ZPC-W is turned on, the heading adjusts following the adaption law to reduce sway force strongly. After $t = 1500s$, the sway force converges to null as the vessel aligns with the current. The overshoot and response time is acceptable, however the actuator has to be very robust at the beginning to induce large sway force during 20 second. Thus, improvement on adaption gain can be made to get a better trade-off between them.

The vessel has some surge and sway motion before $t = 650s$, but not significant. From $t = 650s$ onwards, it keeps steady at null as shown in figure 33.

It is also verified that the heading setpoint and actual heading was adjusted following the adaption law since the yaw angle automatically reaches -2.35 rad ($-\frac{3}{4}\pi$) within around 2000 seconds. That is the optimal heading angle that aligns the vessel with the direction which the current comes. Besides small overshoots on heading setpoint and actual heading, the actual heading follows heading setpoint well. To make improvement, smaller adaption gain is needed, which will sacrifice the settling time instead.

6 Summary

The project showed the usage of reference model, to station-keep the vessel with a given current velocity and to move the vessel to the desired setpoint. The importance of having a reference model and a good controller were observed. Through the simulations one could see that the controller could have been tuned better, especially with respect to yaw. Even though the deviations were small the controller for yaw is slower compared to sway and yaw. Improving the yaw controller would also have made the sway controller better due to the coupling between them. However a trial and error approach was used, one can argue for that there would be some gains that could have made the controller better, since finding the optimal values are nearly impossible by this approach. In addition the deviations were small, largest deviation in the yaw controller in Simulation 1 is ≈ 0.02 rad (figure 8) and that is not that much. Thus even though the controller used a longer time to reach the reference the deviations are almost negligible and therefore therefore the chosen controller gains felt acceptable.

The time constant could have been chosen larger on the yaw as mentioned in the Simulation 3 and 4 since the path following is not as good as for surge and sway. This could have been fixed by modifying the controller for yaw as well, but due to that the reference model dampens out the trajectory the desired path could have been obtained by increasing the time constant.

References

[1] Kim K.M. Lee J. Kim, Y.H. Zero power control with load observer in controlled pm levitation, 2001.

[2] Eduardo A. Tannuri Michel R. Miyazaki. A general approach for dynamic positioning weathervane control, 2013.

[3] Professor Asgeir J. Sørensen. Lecture notes, 2013.