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Autonomous heading control in position mooring with thruster assist

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Introduction

After the Ekofisk discovery in 1969, the oil and gas industry quickly developed into the most dominant industry in Norway. Today, the trend is that the Norwegian offshore industry is experiencing an increased demand for integrated operations with use of marine vessels, both in open waters and in Arctic ice-covered waters. To perform offshore operations, it is required that the vessel has a stationkeeping system in order to maintain a fixed position with high accuracy even in rough environments.

Thrsuter-assisted positioning mooring (TAPM), is a widely used positioning system for automatic thruster assistance of a moored structure. The system has been commercially available since the late 1980s, and is a cost-effective alternative for offshore oil production compared to permanent platforms. Since an TAPM vessel is located in the same position over years, the choice regarding its desired position and heading are extremely important. By using the TAPM system optimal due to the environment, the amount of thrust required will be minimized, leading to a reduced fuel consumption, which in turn will reduce both the operational cost and emission.

The optimal position of a TAPM vessel, is the position where the mean environmental loads acting on the vessel, are balanced by the mooring lines. This position will again depend on the vessels heading. The optimal heading of a vessel is depending on the direction of the mean environmental loads, and is defined as the angle between true north and the vessels direction when the mean environmental loads act through its centre line.

Objective and Scope of Work

This thesis will, through simulation and experiments, try out some new methods for online automatic determination of an optimal setpoint for heading. Two methods inside the theory of Extreemum seeking (ES) has been investigated as a possible method for automatically finding the optimal heading during an operation. These methods are known from other industries, but have until now not been used in TAPM applications.

Below is a picture of an TAPM vessel.

Mathematical Model

In mathematical modeling of the dynamics of a marine vessel, it is common to divide the overall model into two sub-models, a low-frequency (LF) model and a wave-frequency model. The two models are combined through superposition.

A TAPM vessel can be described mathematically by the LF model in equation (1), where $\mathbf{M}_{RB}$ and $\mathbf{M}_A$ are the inertia matrix and the added mass respectively, $\mathbf{C}_{RB}(\boldsymbol{\nu})$ and $\mathbf{C}_A(\boldsymbol{\nu}_r)$ are the Coriolis and centripetal terms and the added mass respectively, $\mathbf{D}(\boldsymbol{\nu}_r)$ is the damping matrix and $\mathbf{G}(\boldsymbol{\eta})$ is the generalized restoring force caused by the buoyancy and gravitation. $\boldsymbol{\nu}_r$ is the relative velocity between the velocity of the ship and the velocity of the water current. The right-hand side of the equation represents the generalized external forces, where $\boldsymbol{\tau}_c$ is the control force provided by the thrusters, $\boldsymbol{\tau}_{env} = \boldsymbol{\tau}_{wave2} + \boldsymbol{\tau}_{wind}$ are the environmental loads due to wind loads and second-order wave drift loads and $\boldsymbol{\tau}_{moor}$ are the mooring forces.

$$\mathbf{M}_{RB}\dot{\boldsymbol{\nu}} + \mathbf{M}_A\dot{\boldsymbol{\nu}} + \mathbf{C}_{RB}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{C}_A(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \mathbf{D}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \mathbf{G}(\boldsymbol{\eta}) = \boldsymbol{\tau}_{env} + \boldsymbol{\tau}_{moor} + \boldsymbol{\tau}_c \quad (1)$$

When deriving a control design model of a surface vessel, it can be assumed that only the motions in the horizontal plan, which are surge, sway and yaw, are of interest.

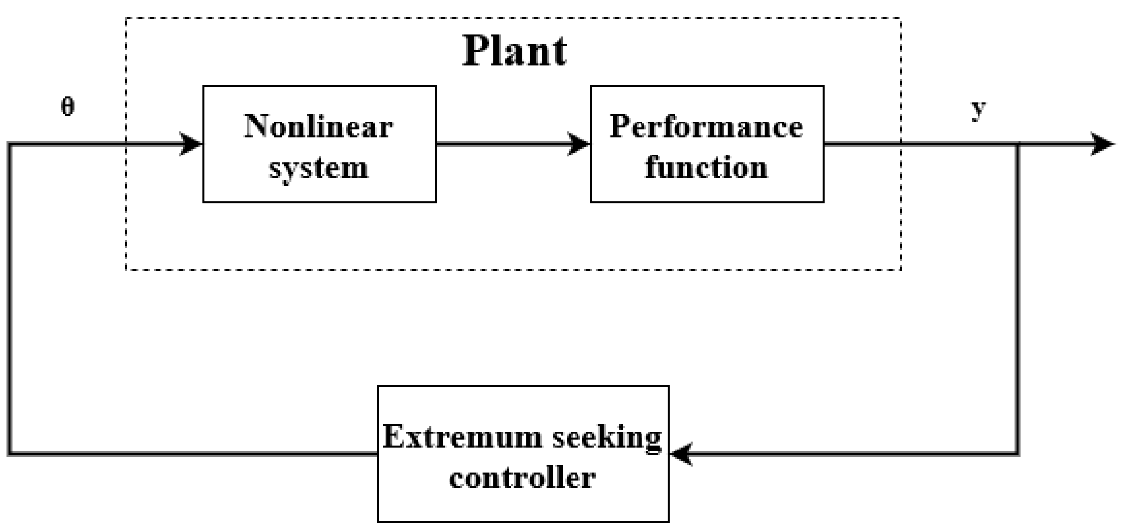
The objective of a controller is to bring the vessel to its desired position and then keep it there. A widely used controller to control a surface vessel is the PID-controller, see (2), where $\dot{\boldsymbol{\xi}} = \boldsymbol{\eta} - \boldsymbol{\eta}_d$, and $\mathbf{K}_{p,i,d}$ are the controller gains, which have to be bigger than zero according to (3).

$$\boldsymbol{\tau}_{PID} = -\mathbf{K}_i\mathbf{R}(\psi)^T\boldsymbol{\xi} - \mathbf{K}_p\mathbf{R}(\psi)^T(\boldsymbol{\eta} - \boldsymbol{\eta}_d) - \mathbf{K}_d(\boldsymbol{\nu} - \boldsymbol{\nu}_d) \quad (2)$$

$$\mathbf{K}_p > 0 \quad , \quad \mathbf{K}_d > 0 \quad , \quad \mathbf{K}_i > 0 \quad (3)$$

All control systems include a guidance system. A guidance system is used to calculate or decide the desired position and heading given to a controller. In this thesis a known guidance system called setpoint chasing is used in order to generate the optimal desired earth-fixed position for surge and sway. In addition, two new designs for autonomous guidance systems for heading have been derived based on the ES theory, which in turn is based on either sinusoidal perturbation or numerical optimization.

The figure below shows a block diagram of a general ES scheme, ans is applicable for both the sinusoidal perturbation method and the numerical optimization based method.



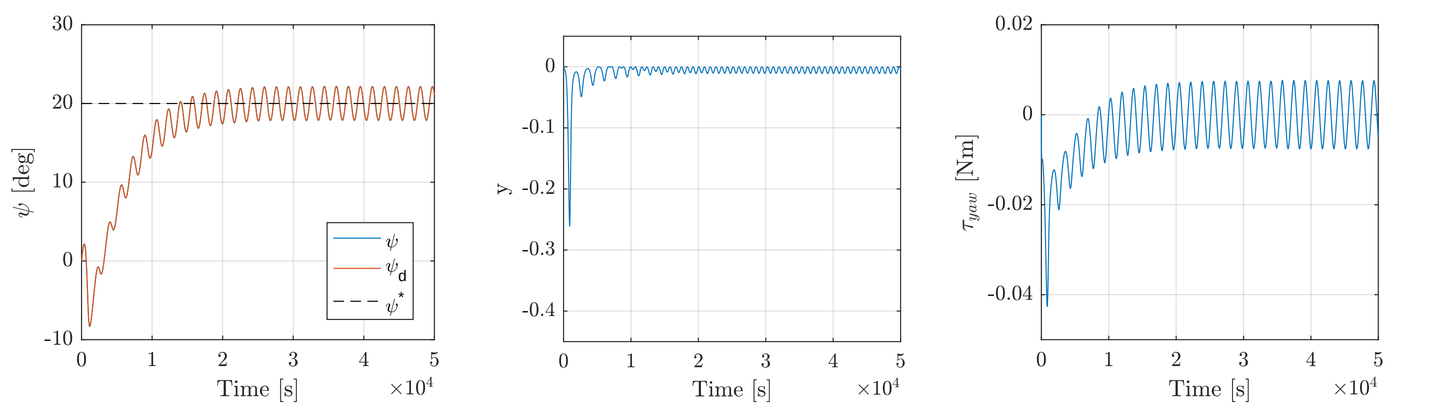
Using ES theory, the plant of the system includes both a nonlinear system and a performance function, where the output of the plant, y, is the performance function. This makes an ES problem into an optimization problem.

The performance function is generally a function of the state and is unknown or poorly known in the ES design. The lack of knowledge implies that the design of the ES controller is only based on the measurement of the performance function. With help of an ES algorithm, it is possible to tune a setpoint for the system based on the measurement of the performance function in order to achieve an optimal value of the output. In other words, the objective and the goal of ES control is to operate at a setpoint that represents the optimal value of a function being optimized in the control loop.

Results and Discussion

Autonomous guidance system based on sinusoidal perturbation based ES

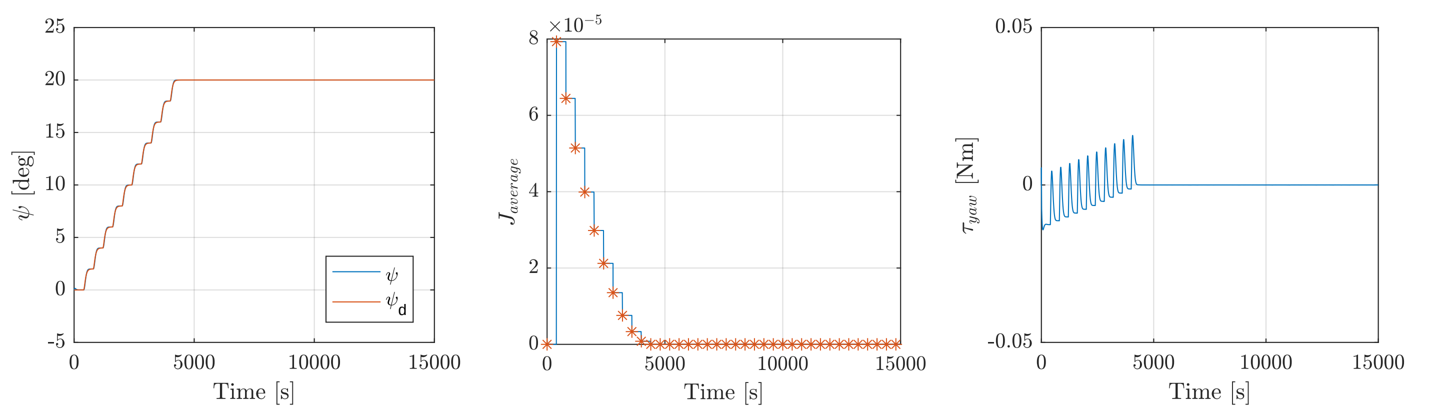
The following plots shows a verification of an autonomous guidance system for heading based on sinusoidal perturbation based ES. The guidance system is estimating a value of the desired heading during a seek for the optimal heading. The performance function for this system is decided to be maximized when $\psi_d = \psi^*$.



As can be seen from the figures above, the measurement of the performance function, y, will increase as the vessel's heading approaches the optimal heading , which in this simulation is 20 degrees. As can be seen from the figures, the controller finds ψ^* after awhile, but because of the perturbation signal added in this method, the ψ_d will oscillate around ψ^* which again will cause oscillations in the vessels heading and thrust.

Autonomous guidance system based on numerical optimization based ES

The following plots shows a verification of an autonomous guidance system for heading based on numerical optimization based ES. The guidance system is estimating a value of the desired heading during a seek for the optimal heading. The performance function for this system is decided to be minimized when $\psi_d = \psi^*$.



As seen in the figures above, the performance function will decrease as ψ_d goes towards ψ^*. At the same time the controller will give zero thrust in yaw, which gives optimal results.

The main drawback from both guidance systems are that they are time consuming.

Conclusion

From the simulation results, it can be concluded that both of the ES methods can be used in order to seek towards the optimal heading. However, the methods will need to be further investigated and optimized in order to be used efficiently for this application.

Acknowledgements

I have received valuable help during this master thesis, and I would like to acknowledge and thank my supervisor and my co-advisors for their contributions.