Nonlinear MPC for Ship Motion Control

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Summary

Autonomous vehicles is a heavily researched area and development is fast, this also applies to the marine industry. In order for a ship to reliably manage complex maneuvers and tasks, while reducing cost by minimizing wear, fuel consumption and the number of installed actuators, smart control algorithms are needed. In this work, a nonlinear MPC is proposed and compared to a commonly used control structure. Results show the benefit of the proposed formulation.

Ship Motion Control

The motion control system (MCS) for overactuated marine vessels is generally divided in two parts, see Fig. 1.

- A high-level motion controller that calculates a desired generalized control force τ_c^d to be exerted on the vessel in order to achieve an objective
- A thruster allocation (TA) algorithm that optimize and distribute the control effort among the thrusters so that the achieved force is equal to the desired

The benefit is a segmented software, aiding in development and commissioning. However, since information regarding physical limitations of the thrusters are hidden from the high-level motion controller, this will result in **sub-optimal control**, and depending on the actuation, deteriorating performance since there typically will be a mismatch between desired and achieved force.

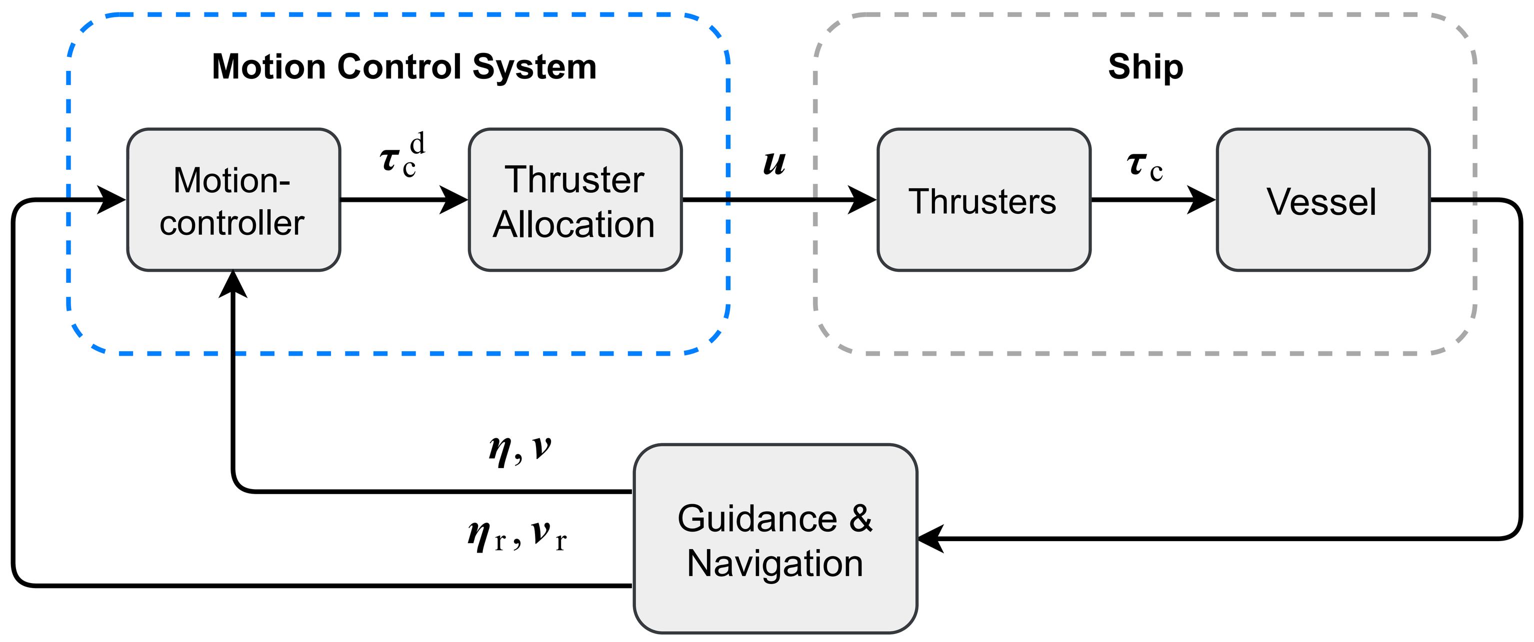


Figure 1: Common ship motion control system hierarchy

Modeling

The motion of the ship is described using two coordinate systems, one body-fixed system and one Earth-fixed system which is assumed to be inertial, see Fig. 2. The body-fixed generalized velocity is described by $\boldsymbol{\nu} = [u\ v\ r]^T$ and the Earth-fixed generalized position is described by $\boldsymbol{\eta} = [x\ y\ \psi]^T$. Here, u is the surge velocity, v is the sway velocity, r is the yaw velocity, x and y is the position in a North-East-Down (NED) coordinate system and ψ is the heading.

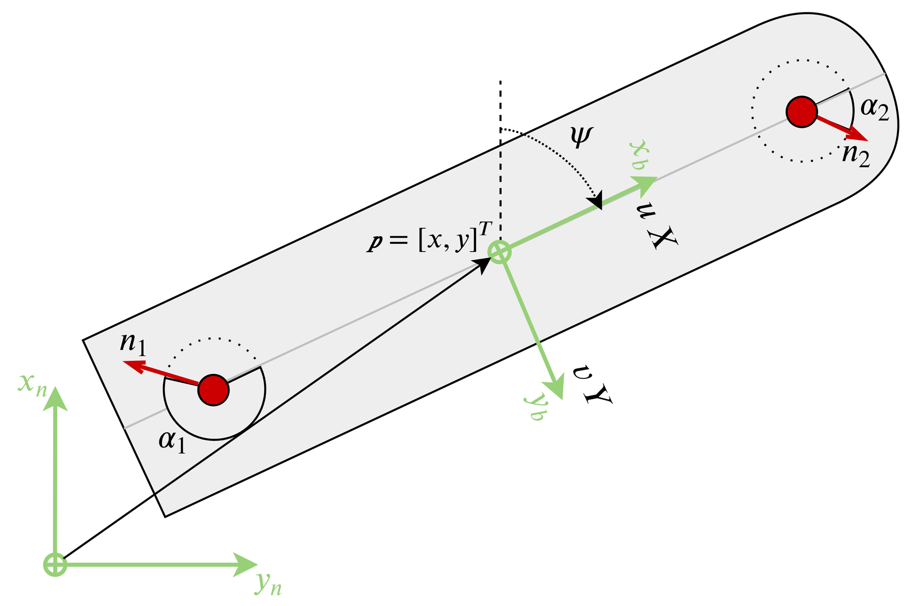


Figure 2: Vessel modeling notation

The relationship between the velocity and the position is purely geometric and is given by

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}(\psi)\boldsymbol{\nu} \tag{1}$$

where $\boldsymbol{R}(\psi)$ is a rotation matrix. A well-known model of the kinetic motion for ships travelling at low speed in 3 DOF is

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{D}\boldsymbol{\nu} = \boldsymbol{\tau}_c \tag{2}$$

where $\boldsymbol{M}$ is the matrix of total inertia including added mass, $\boldsymbol{D}$ is the linear damping matrix and $\boldsymbol{\tau}_c$ is the forces exerted by the thrusters. Restricting the scope to azimuth thrusters, comprising of a propeller mounted on a hub able to rotate freely in the horizontal plane, the forces may be modeled as

$$\boldsymbol{\tau}_c = \boldsymbol{T}(\boldsymbol{\alpha})\boldsymbol{f}(\boldsymbol{n}) \tag{3}$$

where $\boldsymbol{\alpha}$ is a vector of azimuth angles and $\boldsymbol{n}$ the corresponding propeller speeds.

Combining the Algorithms

While the traditional approach is to treat (1) and (2) in the high-level controller, and (3) in the TA separately, they are now combined into a single formulation. Implementation of the controller was done in Simulink using the ACADO toolkit.

MPC Formulation

$$\min_{\dot{n},\dot{\alpha}} \int_0^{T_s N} \left(\|\boldsymbol{\eta} - \boldsymbol{\eta}_r\|^2_{Q_\eta} + \|\boldsymbol{\nu} - \boldsymbol{\nu}_r\|^2_{Q_\nu} + \|\boldsymbol{n}\|^2_{Q_n} + \|\dot{\boldsymbol{\alpha}}\|^2_{Q_{d\alpha}} + \|\dot{\boldsymbol{n}}\|^2_{Q_{dn}} \right) dt + \text{final cost} \tag{4a}$$

$$\text{s.t.}\quad \dot{\boldsymbol{\eta}} = \boldsymbol{R}(\psi)\boldsymbol{\nu} \tag{4b}$$

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{D}\boldsymbol{\nu} = \boldsymbol{T}(\boldsymbol{\alpha})\boldsymbol{f}(\boldsymbol{n}) \tag{4c}$$

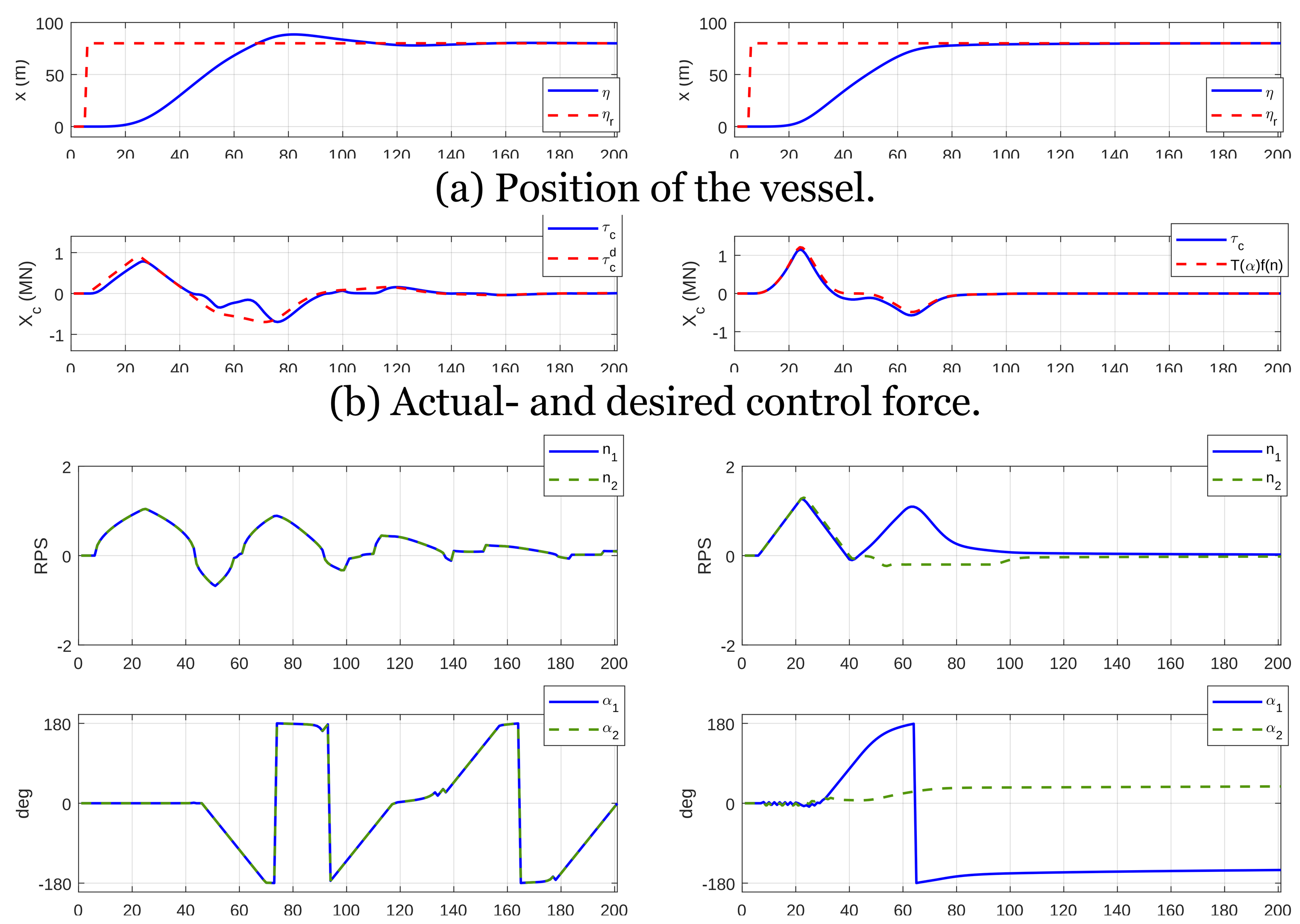
$$\underline{\boldsymbol{n}} \le \boldsymbol{n} \le \bar{\boldsymbol{n}} \tag{4d}$$

$$|\dot{\boldsymbol{\alpha}}| \le \bar{\dot{\boldsymbol{\alpha}}} \tag{4e}$$

$$\underline{\dot{\boldsymbol{n}}} \le \dot{\boldsymbol{n}} \le \bar{\dot{\boldsymbol{n}}} \tag{4f}$$

Simulation

Results comparing the proposed controller with a decoupled MCS using a MPC high-level controller and an one-step TA. The simulated ship is 82.8 m long, 19.2 m wide, has a displacement of 6360 tonnes and is equipped with two azimuth thrusters as in Fig. 2. At $t = 8$s, $\boldsymbol{\eta}_r = [0\ 0\ 0]^T \rightarrow [80\ 0\ 0]^T$ while the velocity reference is $\boldsymbol{\nu}_r = \boldsymbol{0}$. Note the force mismatch and subsequent overshoot of the target point for the decoupled approach, occuring due to the inability to brake the ship efficiently with both thrusters pointing forward.



(a) Position of the vessel.

(b) Actual- and desired control force.

(c) Controls of the thrusters.

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