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Comparing Controllers for Dynamic Positioning of Ships in Extreme Seas

Ole M. R. Rabanal * **Astrid H. Brodtkorb** ** **Morten Breivik** *

* *Department of Engineering Cybernetics (e-mail: ole.roeste@gmail.com, morten.breivik@ieee.org).*
** *Centre for Autonomous Marine Operations and Systems, Department of Marine Technology (e-mail: astrid.h.brodtkorb@ntnu.no). Norwegian University of Science and Technology (NTNU), NO-7491, Trondheim, Norway*

Abstract: This paper considers the design, implementation and experimental verification of two controllers for ship station keeping in extreme seas. In particular, the performance of two dynamic positioning controllers are compared, namely a sliding mode controller and a PID controller with acceleration feedback. The former has been tested in extreme seas before because the acceleration feedback term virtually increases the inertia of the ship, making it less sensitive to large wave loads. Sliding mode control is chosen because of its robustness to parameter uncertainties such as frequency dependency of added mass and damping. Model-scale experiments are performed in the Marine Cybernetics Laboratory at the Norwegian University of Science and Technology. The performance is measured by new performance metrics combining the energy consumption from thrusters onboard the ship with position and heading precision.

Keywords: Dynamic positioning, station keeping, extreme seas, PID, acceleration feedback, sliding mode control, performance metrics, model-scale experiments, energy efficiency

1. INTRODUCTION

Marine operations are becoming more challenging due to operations in deeper waters, further from shore, where the sea state often can be characterized as extreme, with large waves and wind gusts. With such environmental effects, the need for dynamic positioning (DP) vessels with enhanced positioning capabilities increases. The authors are therefore motivated to find a safer, smarter and greener DP algorithm for maintaining safety of personnel and cargo while at the same time ensuring an energy efficient operation. In extreme seas, large motion couplings in six degrees of freedom (DOF) occur and it is therefore important to have a robust controller.

Sea states with significant wave height $H_s \geq 3.5$ m and peak period of waves $T_p \geq 10$ s are here referred to as extreme seas. Such sea states, or higher, occur roughly 30% of the time in the Northern North Atlantic. When extreme seas occur, waves are higher and have longer periods so that the wave-frequency (WF) motions are found in the same frequency regime as the low-frequency (LF) motions of the vessel. This will cause a challenge for an estimator separating the LF from the WF motions using a wave filter, because the wave filter removes important LF vessel motions that the controller should compensate for. To solve this problem, Sørensen et al. (2002) proposed to neglect the wave filter for extreme seas in order to maintain performance and stability. This has been tested by Nguyen et al. (2007) and Brodtkorb et al. (2014) with the use of hybrid controllers in simulations and experiments with a model-scale ship. The hybrid controller implemented in both works include proportional-integral-derivative control with acceleration feedback (PID-AFB) and a nonlinear passive observer (NPO) without wave filtering. By comparing simulations of the hybrid controller with a single PID controller with wave filtering, in a sea state varying from calm to extreme seas, the hybrid controller provided best performance. A PID-AFB controller was first proposed by Lindegaard (2003), where a virtual inertia is added to the physical inertia and increased by using feedback of the measured acceleration of the system.

Sliding mode control (SMC) is recognized as an efficient tool for designing robust controllers for complex high-order nonlinear dynamic plants operating under uncertain conditions. SMC has been adapted and used for multiple-input, multiple-output (MIMO) nonlinear systems by Slotine and Li (1991) and extended by Fossen and Foss (1991), with the idea of designing a robust controller in the case of unmodeled dynamics and modeling inaccuracies of parameters such as inertia, external loads and actuators. The robustness of the SMC algorithm is here achieved by introducing uncertainties to the parameters added mass and damping.

The main contributions of this paper include the implementation and experimental testing of two DP control algorithms on a model-scale ship and evaluating performance by applying new performance metrics. The performance metrics include the pose (position and heading) accuracy and energy consumption by the thrusters. Experiments with the ship model in different sea states were conducted in the Marine Cybernetics Laboratory

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(MCLab) comparing the performance of PID-AFB and SMC in DP when exposed to extreme seas. More details from the experiments can be found in (Rabanal, 2015).

The paper is organized as follows: Section 2 presents the mathematical modeling of the ship and a model-based observer; Section 3 describes the design of the PID-AFB and SMC controllers; Section 4 describes the lab setup, test cases, parameter tuning and performance metrics; Section 5 presents the results and discussion, Section 6 concludes the paper and the acknowledgments are found in Section 7.

2. MATHEMATICAL MODELING

This section considers mathematical modeling of marine vessels and a model-based observer for extreme seas.

2.1 Control Plant Model (CPM)

A control plant model (CPM) is a mathematical model describing only the most important physical properties of a dynamical process and is used for model-based observer and controller design Sørensen (2013).

In sea states with peak wave periods from 5-9 seconds, corresponding to sea state codes calm-rough (Price and Bishop, 1974), a DP control system counteracts low-frequency (LF) wave motions caused by wind, current and slowly-varying wave loads. It is common to filter out the wave-frequency (WF) vessel motions from the measurements caused by first-order wave loads in order to avoid wear and tear of the propulsion system.

When the vessel experiences extreme seas, such an observer wave filter will remove important LF vessel motions, leading to poor estimates of the pose. Maintaining pose when the vessel is experiencing motions due to large waves then becomes a challenge. Such waves have long periods and are most likely generated by wind (Fossen, 2011). Sørensen et al. (2002) proposes to solve this problem by reformulating the CPM by neglecting the WF model. When disabling the wave filter, the controller has to compensate for both LF and WF motions, which will cause more sudden movements and increased thrust in the corresponding directions.

A CPM for DP in extreme seas (Sørensen et al., 2002) is:

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

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} = -\boldsymbol{D}\boldsymbol{\nu} + \boldsymbol{R}^\top(\psi)\boldsymbol{b} + \boldsymbol{\tau} \tag{1b}$$

$$\dot{\boldsymbol{b}} = -\boldsymbol{T}_b^{-1}\boldsymbol{b} + \boldsymbol{E}_b\mathbf{w}_b \tag{1c}$$

$$\mathbf{y} = \boldsymbol{\eta} + \mathbf{v}, \tag{1d}$$

where $\boldsymbol{\eta} \in \mathbb{R}^3$ is the position and heading (pose) vector and the velocity vector is written as $\boldsymbol{\nu} \in \mathbb{R}^3$. The rotation matrix $\boldsymbol{R}(\psi) \in \mathbb{R}^{3\times3}$ transforms the velocity from the body-fixed to the north-east-down (NED) reference frame. A bias model with state $\boldsymbol{b} \in \mathbb{R}^3$ represents slowly-varying environmental forces and is driven by the zero-mean Gaussian white noise vector $\mathbf{w}_b \in \mathbb{R}^3$ with the disturbance scaling matrix $\boldsymbol{E}_b \in \mathbb{R}^{3\times3}$. In addition, $\boldsymbol{T}_b \in \mathbb{R}^{3\times3}$ is a user-specified diagonal matrix of positive bias time constants. The matrix $\boldsymbol{M} \in \mathbb{R}^{3\times3}$ is the inertia matrix consisting of the rigid-body and added-mass terms, while linear damping is represented by the matrix $\boldsymbol{D} \in \mathbb{R}^{3\times3}$. The commanded forces and moment vector $\boldsymbol{\tau} \in \mathbb{R}^3$ is generated by the controller, and the measurement from sensor output is written as $\mathbf{y} \in \mathbb{R}^3$. The measurement noise vector is $\mathbf{v} \in \mathbb{R}^3$.

2.2 Nonlinear Passive Observer (NPO)

The observer is an important part of a DP system because of its capabilities of state estimation and filtering. If sensors become faulty or too expensive, the observer can perform state estimation of non-measured states. If the vessel experiences signal losses because of sensor failure, one can use dead reckoning and trust the prediction model in the observer.

The following observer without wave filtering is proposed by Sørensen et al. (2002) for extreme seas:

$$\dot{\hat{\boldsymbol{\eta}}} = \boldsymbol{R}(\mathrm{y})\hat{\boldsymbol{\nu}} + \boldsymbol{K}_1\tilde{\mathbf{y}} \tag{2a}$$

$$\dot{\hat{\boldsymbol{b}}} = -\boldsymbol{T}_b^{-1}\hat{\boldsymbol{b}} + \boldsymbol{K}_2\tilde{\mathbf{y}} \tag{2b}$$

$$\boldsymbol{M}\dot{\hat{\boldsymbol{\nu}}} = -\boldsymbol{D}\hat{\boldsymbol{\nu}} + \boldsymbol{R}^\top(\mathrm{y})\hat{\boldsymbol{b}} + \boldsymbol{\tau} + \boldsymbol{R}^\top(\mathrm{y})\boldsymbol{K}_3\tilde{\mathbf{y}} \tag{2c}$$

$$\hat{\mathbf{y}} = \hat{\boldsymbol{\eta}}, \tag{2d}$$

where $\hat{\boldsymbol{\eta}}$ and $\hat{\boldsymbol{\nu}}$ are the estimated pose and velocity vectors, $\hat{\boldsymbol{b}}$ is the estimated bias state, $\hat{\mathbf{y}}$ is the estimated output, while matrices such as $\boldsymbol{M}$ and $\boldsymbol{D}$ are given above. The rotation matrix is written as $\boldsymbol{R}(\mathrm{y}) = \boldsymbol{R}(\psi)$ and $\boldsymbol{K}_1 \in \mathbb{R}^{3\times3}$, $\boldsymbol{K}_2 \in \mathbb{R}^{3\times3}$ and $\boldsymbol{K}_3 \in \mathbb{R}^{3\times3}$ are positive definite observer gain matrices.

3. CONTROLLER DESIGN

This section presents the control design of PID with acceleration feedback (PID-AFB) and sliding mode control (SMC) algorithms for generating the control input $\boldsymbol{\tau}$.

3.1 PID with Acceleration Feedback (PID-AFB)

This subsection is inspired by Fossen et al. (2002) and Lindegaard (2003). The PID-AFB controller is different from the conventional PID controller due to an extra inertia term $\boldsymbol{K}_m$ that is fed back with measured acceleration and added to the system inertia matrix $\boldsymbol{M}$. This makes the system less sensitive to external disturbances and hence more robust. The control input $\boldsymbol{\tau}$ from (1b) is generated by the following control law:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{PID-AFB} = \boldsymbol{R}^\top(\psi)\boldsymbol{\tau}_{PID} - \boldsymbol{K}_m\dot{\boldsymbol{\nu}}, \tag{3}$$

with

$$\boldsymbol{\tau}_{PID} = -\boldsymbol{K}_p\tilde{\boldsymbol{\eta}} - \boldsymbol{R}(\psi)\boldsymbol{K}_d\boldsymbol{\nu} - \boldsymbol{K}_i\int_0^t \tilde{\boldsymbol{\eta}}(\tau)\,\mathrm{d}\tau. \tag{4}$$

The control objective is to force $\tilde{\boldsymbol{\eta}} \to \mathbf{0}$ when $t \to \infty$, where $\tilde{\boldsymbol{\eta}} = \boldsymbol{\eta} - \boldsymbol{\eta}_d$ is the error between the actual and desired pose. As the aim is station keeping, the desired pose is constant and $\dot{\boldsymbol{\eta}}_{\boldsymbol{d}} \approx \mathbf{0}$. The positive definite gain matrices $\boldsymbol{K}_p \in \mathbb{R}^{3\times3}$, $\boldsymbol{K}_d \in \mathbb{R}^{3\times3}$ and $\boldsymbol{K}_i \in \mathbb{R}^{3\times3}$ belong to the PID-part of the controller.

The AFB gain matrix $\boldsymbol{K}_m \in \mathbb{R}^{3\times3}$ is chosen as proposed by Fossen et al. (2002) with $\boldsymbol{K}_m = \boldsymbol{M}^* + \Delta\boldsymbol{K}$, where $\boldsymbol{M}^*$