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An Output Feedback Controller with Improved Transient Response of Marine Vessels in Dynamic Positioning ⋆

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Abstract: An output feedback controller for dynamic positioning (DP) of marine surface vessels is developed. The proposed algorithm has good performance during transients as well as good steady state performance. The method achieves this by a flexible injection gain in the bias estimation dynamics in the observer. In addition, the traditional integral action is replaced by a filtered bias estimate from the observer. Both these elements combined provide good DP performance in transients, as well as calm behavior in steady state. A simulation study is performed showing the benefit of the proposed output feedback controller, and a stability analysis is performed to show uniform asymptotic stability.

Keywords: Dynamic positioning; Observers; Output feedback; Integral action

1. INTRODUCTION

A surface vessel performing dynamic positioning (DP) has to keep position and orientation (stationkeeping) or do low speed tracking while compensating for the slowly-varying loads that affect the vessel. These loads are typically due to current, mean wind loads, and second order wave loads. The sum of these loads together with unmodeled dynamics, is lumped into the bias load vector. For model-based observer designs it is important to estimate this bias in order to achieve good estimation of the velocity, and thereby the position of the vessel. In addition, this bias load needs to be compensated in the controller to keep the desired position. This is typically achieved through integral action in the control law.

In standard model-based observer designs (Fossen, 2011), the tuning of the bias observer is set low to ensure good performance of the observer in steady state. Since the bias is typically slowly-varying, low tuning will lead to less oscillations in the bias estimate, and therefore also less oscillations in the velocity and position estimates. However, when there is a significant transient in the bias force, for instance by a heading change, a wave train, or a mooring line that breaks (for position mooring), the bias estimate will take some time to converge to the new value. This is problematic for transient performance of the DP system, since the velocities will not be estimated correctly over the course of the transient.

The objective of this paper is to construct a model-based observer and controller with good performance in both transients as well as in steady state. This will be achieved by two changes from the standard model-based design. The first is to allow for a flexible bias estimation in the observer. The injection gain in the bias dynamics will be allowed to take values ranging from a nominal gain matrix to higher gains and a more aggressive tuning. The second contribution is to add a lowpass-filtered bias estimate which has a less oscillatory and smoother characteristics than the direct bias estimate. This filtered estimate will be used to compensate for the bias in the controller. There are two reasons for this implementation. From the literature, the two existing options for compensating the bias is to either use the bias estimate from the observer (Loría and Panteley, 1999), or to add integral action in the controller (Sørensen, 2011). The integral action in the controller finds the bias estimate based on the tracking errors. Since the control performance depends on the convergence of the observer, it is reasonable to believe that the bias estimate in the observer will always be faster than the integral action based on tracking errors (with reasonable tuning).

However, if we use a filtered version of the bias estimate, we allow for fast bias convergence in the observer, without having to send this noisy estimate directly to the controller. At the same time the bias compensation term in the controller is oscillating less than the direct bias estimate itself, and this is most likely faster than integral action based on tracking errors. This is a similar idea as used in L1 adaptive control (Hovakimyan and Cao, 2010).

In addition, there is a tuning benefit of using the bias estimate from the observer, both because tuning an ob-

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server does not require the system to be in closed loop, and because tuning of integral action (on tracking errors) heavily depends on how fast the observer estimates converge. This is especially beneficial in the current design, since the proposed observer have time-varying gains.

Similar use of time-varying gains is present in the literature. See for instance Tutturen and Skjetne (2015) where hybrid integral action for DP of marine vessels is proposed, and Lekkas and Fossen (2014) where the authors propose to use a time-varying lookahead distance as a function of the cross track error in a line-of-sight algorithm. In Belleter et al. (2013, 2015) a wave encounter frequency estimator is proposed, where the frequency adaption law has a time-varying gain. In Bryne et al. (2014) time-varying gains are proposed for an inertial observer (aided by GNSS) for DP, in order to improve convergence and suppress sensor noise.

2. PROBLEM FORMULATION

In the following we will separate between a simulation model and a control design model. The simulation model has higher fidelity and is used for simulation and verification of observer and control designs. Because of the low-speed nature of the dynamic positioning operations, the control design models typically neglect centripetal and Coriolis terms, as well as nonlinear damping; see (Sørensen, 2005, 2011), and (Fossen, 2011). The control design model considered here is a horizontal motion 3 degree of freedom (DOF) model, with the dynamics

$$\dot{\xi} = A_w \xi + E_w w_w \quad (1a)$$
$$\dot{\eta} = R(\psi)\nu \quad (1b)$$
$$\dot{b} = w_b \quad (1c)$$
$$M\dot{\nu} = -D\nu + R(\psi)^\top b + u \quad (1d)$$
$$y = \eta + C_w \xi + v_y, \quad (1e)$$

where $\xi \in \mathbb{R}^6$ is the state of a synthetic white noise-driven model of the vessel motion due to the 1st order wave loads. In normal operating conditions it is beneficial to counteract the low frequency part of the wave motion only, and the model therefore consists of a wave model (1a) and a low frequency part (1b) - (1d), which consists of the low frequency position in north and east, as well as the heading angle, $\eta := [N, E, \psi]^\top \in \mathbb{R}^3$, the velocities in surge, sway, and the yaw rate, $\nu := [u, v, r]^\top \in \mathbb{R}^3$, the slowly varying NED-fixed bias force $b \in \mathbb{R}^3$ that constitutes the sum of all slowly-varying perturbation loads, such as current, mean wind, 2nd order waves, and unmodeled dynamics. In (1b) the kinematic relation is described by the 3 DOF rotation matrix from the body to the NED frame $R(\psi) \in \mathbb{R}^{3\times 3}$,

$$R(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (2)$$

and the time derivative of $R(\psi)$ is given by $\dot{R} = rS$, where

$$S = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad (3)$$

and $r = \dot{\psi} \in \mathbb{R}$ is the yaw rate. In (1d), $M \in \mathbb{R}^{3\times 3}$ is the inertia matrix including added mass, $D \in \mathbb{D}^{3\times 3}$ is the linear damping matrix, and $u \in \mathbb{R}^3$ is the control input vector. The measurements $y \in \mathbb{R}^3$ in (1e) measure the actual position of the vessel, that is, the sum of the low frequency and wave frequency position, where $C_w = [0\ I] \in \mathbb{R}^{3\times 6}$, and $v_y \in \mathbb{R}^3$ is the measurement noise.

The control objective of the paper is to construct an output feedback tracking controller for DP, that has good performance in both steady state as well as in transients. This output feedback controller will track a reference trajectory given by an open-loop reference system (Sørensen, 2011).

Below are some assumptions relevant for the observer and control design.

Assumption 1. Starboard/port symmetry, $M = M^\top > 0$, and $\dot{M} = 0$. The damping matrix satisfies $D + D^\top > 0$.

Assumption 2. Because of physical limitations of the thrusters, the yaw rate is bounded, by $|r| \le r_{max} < \infty$.

3. OUTPUT FEEDBACK DESIGN

3.1 Model-based observer

The model-based observer considered is similar to the traditional "nonlinear passive observer" presented in Fossen and Strand (1999) with an additional state $\hat{b}_f$, which is a lowpass-filtered version of $\hat{b}$. By copying the dynamics of (1), neglecting the noise terms, and adding injection terms we get the observer dynamics as

$$\dot{\hat{\xi}} = A_w \hat{\xi} + K_{1,\omega} \bar{y} \quad (4a)$$
$$\dot{\hat{\eta}} = R(\psi)\hat{\nu} + K_2 \bar{y} \quad (4b)$$
$$\dot{\hat{b}} = K_3 \bar{y} \quad (4c)$$
$$\dot{\hat{b}}_f = -T_f^{-1}[\hat{b}_f - \hat{b}] \quad (4d)$$
$$M\dot{\hat{\nu}} = -D\hat{\nu} + R(\psi)^\top \hat{b} + u + K_4 R(\psi)^\top \bar{y} \quad (4e)$$
$$\hat{y} = \hat{\eta} + C_w \hat{\xi}, \quad (4f)$$

where $\hat{\xi} \in \mathbb{R}^6, \hat{\eta}, \hat{b}, \hat{b}_f, \hat{\nu} \in \mathbb{R}^3$ are the state estimates, $K_{1,\omega} \in \mathbb{R}^{6\times 3}, K_2, K_3, K_4 \in \mathbb{R}^{3\times 3}$ are non-negative gain matrices, and $\bar{y} = y - \hat{y}$ is the measurement error. The underlying assumptions for the observer are:

Assumption 3. (a) $R(\psi + \psi_w) \approx R(\psi)$. That is, the heading angle due to wave-induced motion is small.
(b) The frequency used in the wave filter does not change. It corresponds to the peak frequency of the wave spectra of the incoming sea state.

By defining the estimation error states $\bar{\eta} := \eta - \hat{\eta}$, $\bar{\nu} := \nu - \hat{\nu}$, $\bar{b} := b - \hat{b}$, $\bar{b}_f := b - \hat{b}_f$, and subtracting the observer equations (4) from the control design model (1), we get the observer error system,

$$\dot{\bar{\xi}} = A_w \bar{\xi} - K_{1,\omega} \bar{y} \quad (5a)$$
$$\dot{\bar{\eta}} = R(\psi)\bar{\nu} - K_2 \bar{y} \quad (5b)$$
$$\dot{\bar{b}} = -K_3 \bar{y} \quad (5c)$$
$$\dot{\bar{b}}_f = -T_f^{-1}[\bar{b}_f - \bar{b}] \quad (5d)$$
$$M\dot{\bar{\nu}} = -D\bar{\nu} + R(\psi)^\top \bar{b} - K_4 R(\psi)^\top \bar{y}. \quad (5e)$$