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# Hybrid observer for improved transient performance of a marine vessel in dynamic positioning ⋆

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**Abstract:** Dynamic positioning (DP) systems are used on marine vessels for automatic station keeping and tracking operations solely by use of thrusters. Observers are key components of DP systems, and two main types are proposed in this paper. The model-based type is used in steady state conditions since it is especially good at filtering out first order wave induced motions and predicting states in the case of signal loss, and the signal-based type typically has superior performance during transients. In this paper a hybrid observer including a signal-based part and a model-based part with a performance monitoring function is proposed. The observer part that provides the best estimate of the vessel position and heading is used in closed-loop control, thereby allowing for improved transient response while maintaining good steady-state performance. The contributions of this paper include the design of a hybrid signal-based and model-based observer with performance monitoring, stability analysis of the vessel with hybrid estimates in output feedback control, and simulations of a platform supply vessel during a setpoint and heading change.

*Keywords:* Dynamic positioning, observers, hybrid systems, output feedback control

## 1. INTRODUCTION

Marine operations are moving further from shore and into harsher environments, and with it requirements for the DP vessel's operational window, safety functions and energy-efficiency become stricter. Vessels that are doing operations with longer duration experience changing sea states with varying wind and wave directions, with suboptimal heading at times. Large forces and moments act on the vessel, making quick and precise control essential, especially when operating close to other offshore infrastructures.

There are many unknown factors at sea that may cause transients in the vessel response depending on the type of operations: wave trains, ice loads, mooring line break, etc. However, many transients are triggered by the operator, which makes them easier to account for with proactive control strategies, e.g. heading and setpoint changes, pipelay operations, well intervention operations, the lowering of a jack-up vessel from jacked-up to floating, etc. In this work the transient response of a DP vessel is improved by combining two observers.

The model-based observer, like the Extended Kalman filter (Tannuri and Morishita, 2006), (Hassani et al., 2013), or the nonlinear passive observer (Fossen and Strand, 1999), are commonly used in DP systems. The model-based observer uses noisy position and heading angle measurements to estimate the low frequency position, heading, and velocity of the vessel. A key feature of this observer type is the wave filter, which eliminates the wave frequency vessel motion from the output feedback control law. This reduces the wear and tear on the machinery as well as reducing the energy consumption.

The signal-based observer, also referred to as a kinematic, or sensor-based observer, is based on the kinematic equations, see for instance Mahony et al. (2008), Hua (2010), Grip et al. (2012), and Bryne et al. (2015). It is especially well suited during transients, as it uses linear acceleration measurements to predict velocity and position. In this implementation no wave filter was included in this observer, but it is ongoing work by Bryne et al. (2016). As a result this observer estimates the total vessel motion, including low frequency and wave frequency motion. When inserted into the control law it gives an oscillatory thrust command.

Earlier hybrid control theory has been applied to dynamic positioning in a changing sea state, see Nguyen et al.

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(2007) and Brodtkorb et al. (2014), and for changing operational modes (Nguyen et al., 2008). These all consist of a bank of controllers and observers with a supervisory mechanism that monitors performance and chooses the best controller/observer pair. Dwell-time and hysteresis switching were applied to avoid chattering. In this paper we apply an output feedback DP controller, using analysis from Loria et al. (2000). Related to this, Prieur and Teel (2011) looks at output feedback control using a hybrid controller with a nonlinear globally stabilizing part, and a linear locally stabilizing part.

The main contributions of this paper includes the design, analysis, and simulation of a hybrid observer with a model-based part and a signal-based part for improving the transient vessel response in an uncertain marine environment. A performance monitoring function keeps track of the mean estimation error over a time period for the observers, and the estimates from the better-performing observer are used in closed-loop output feedback control using a nonlinear proportional, integral, derivative (nPID) controller. Hysteresis is applied in order to limit the number of jumps for the system, and this is important for the stability of the system.

The organization of the paper is as follows: In Section 2 typical instrumentation for DP vessels is discussed, and two mathematical models of marine DP vessels are presented. A model-based and a signal-based observer are introduced in Section 3, and Section 4 presents the output feedback control algorithm. The hybrid signal-based and model-based observer in closed loop control is modeled in Section 5, and stability is discussed in Section 6. Simulation results for a platform supply vessel doing a setpoint change are presented and discussed in Section 7. Section 8 concludes the paper.

## 2. MARINE VESSEL MODELING AND DYNAMIC POSITIONING

Two reference frames are used in this paper: the North-East-Down (NED) reference frame which is a local Earth-fixed frame, and the body frame, which is body-fixed.

### *2.1 Instrumentation*

DP vessels have statutory class requirements on the onboard instrumentation, and system redundancy. Vessels have positioning systems, e.g. GNSS, acoustics, or laser, a compass measuring heading angle, and an inertial measurement unit (IMU) that combines gyroscopes for measuring angular rates and accelerometers for measuring linear acceleration. The measurements are taken at different sampling rates ranging from 0.1-2 Hz for acoustics, 0.5-4 Hz for GNSS position measurements, to 100-200 Hz for IMU angular velocity and acceleration measurements. The measurements are in this paper assumed to be of the form

$$p^n = [N, E]^\top \tag{1a}$$
$$\psi_c = \psi \tag{1b}$$
$$\omega^b_{imu} = \omega^b + b_g \tag{1c}$$
$$f^b_{imu} = R(\Theta)(\dot{v}^n - g^n), \tag{1d}$$

where the measurements in the NED frame have superscript $n$, and measurements in the body frame have superscript $b$. $p^n \in \mathbb{R}^2$ is the measured position in north and east. A heave measurement may also be obtained through GNSS, but it is typically of low quality and is not used here. $\psi_c \in \mathbb{R}$ is measured heading angle ($\psi$ is used in the remainder of the paper), $\omega^b_{imu} \in \mathbb{R}^3$ is measured angular rate $\omega^b$, $f^b_{imu} \in \mathbb{R}^3$ is measured linear acceleration, $\Theta = [\phi,\ \theta,\ \psi]^\top \in \mathbb{R}^3$ is the orientation in roll, pitch and yaw, $R(\Theta) \in \mathbb{R}^{3\times3}$ is the rotation matrix about the $z, y, x$ axes, $g^n \in \mathbb{R}^3$ is acceleration due to gravity, and $b_g \in \mathbb{R}$ is the gyro bias. Measurement noise is disregarded in the stability analysis, but inserted in simulations.

### *2.2 Marine vessel modeling*

Two models of the same system are presented.

*Control plant model* The control plant model for a vessel is a simplification of the real vessel dynamics. It is different for the various vessel types, operational and environmental conditions, and the design problem under consideration (e.g. observer design or feedback control design); see Fossen (2011) or Sørensen (2013). A surface vessel in DP with starboard/port symmetry, $M = M^\top$, has largest motions in the horizontal plane (surge, sway, and yaw), so the heave, roll, and pitch dynamics are neglected. The control plant model in this case is:

$$\dot{\xi} = A_w\xi + E_w w_w, \tag{2a}$$
$$\dot{\eta} = R(\psi)\nu, \tag{2b}$$
$$\dot{b} = -T_b^{-1}b + E_w w_b \tag{2c}$$
$$M\dot{\nu} = -D\nu + R^\top(\psi)b + u, \tag{2d}$$
$$y = \eta + W\xi + v_y; \tag{2e}$$

where the states of the system include the 3 DOF North, East position and heading $\eta := [N, E, \psi]^\top$ and body-fixed velocity $\nu$ in surge, sway and yaw. In normal operational conditions we want to control only the low frequency part of the vessel motion, and the wave filter in (2a) allows us to separate the motion into a wave frequency part, and a low frequency part. The wave filter has a state $\xi \in \mathbb{R}^6$ and system matrix $A_w \in \mathbb{R}^{6\times6}$ that contains the peak wave frequency and damping. It is driven by zero mean white noise $w_w$. (2b-d) are the low frequency dynamics of the vessel. (2b) is the 3 DOF kinematics that transforms velocity from the body to the NED frame; $R(\psi)$ is the rotation matrix about the $z$-axis,

$$R(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{3}$$

The wave frequency part of the heading angle, $\psi_w$, is assumed to be small, $R(\psi+\psi_w) \approx R(\psi)$. (2c) is a bias force model with state $b \in \mathbb{R}^3$, accounting for *slowly-varying* environmental disturbances from mean wind, current, and second-order wave loads and unmodeled vessel dynamics. $T_b$ is the Markov time constant, and $w_b$ zero mean white noise. Note that the bias force model does not capture rapidly varying disturbances. In (2d) $M \in \mathbb{R}^{3\times3}$ is the inertia matrix including added mass for asymptotic values of wave frequency equal to zero, $D \in \mathbb{R}^{3\times3}$ is the linear damping coefficient matrix, and $u \in \mathbb{R}^3$ is the control input. (2e) is the measurement $y = [(p^n)^\top\ \psi]^\top \in \mathbb{R}^3$ of