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A Robust Dynamic Positioning Tracking Control Law Mitigating Integral Windup ⋆

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Abstract: This paper deals with the design of a tracking control law for dynamic positioning of marine vessels subject to disturbances. It shows that the integral windup problem can be mitigated by removing the position setpoint in the proportional error term and injecting the velocity setpoint in the integral state. This creates an internal reference point in the control law for the vessel to follow. Control of the transient convergence trajectories is achieved without compromising stability by constraining the internal convergence velocity. The proposed control law provides the same functionality as a conventional tracking control law in combination with a reference filter, but with lower complexity and fewer tuning parameters. A closed-loop simulation case study verifies the theoretical findings and show feasible and robust performance.

Keywords: Nonlinear control design; Integral windup; Setpoint tracking; Dynamic positioning

1. INTRODUCTION

Dynamic positioning (DP) of a marine vessel is defined as keeping location (either a fixed position and heading or low-speed tracking) exclusively by means of onboard thrusters (IMO, 1994). State-of-the-art marine control systems employ the structure of Figure 1 and are designed using continuous model-based control methods relying on measurements of position, heading, and sometimes angular velocity (Fossen, 2011; Sørensen, 2012). Since the 1960's the control law principle has relied on proportional position and damping terms together with integral action in PID-like structures to calculate forces and moments needed for positioning (Breivik et al., 2015). Proportional feedback is still state-of-the-art, but modern designs include nonlinear terms to handle reference frame transformations and guarantee stability. Although such control laws have good track record in most sea states, the nonlinear PID structure has issues with respect to integral windup and integral settling time during setpoint changes.

To avoid overshoot, oscillations, and instabilities, integral windup is typically dealt with by slow integral action update together with a reference filter providing a smooth time-varying reference trajectory. Additional remedies such as bounding the integral action output and integrator resetting may also be applied (Sørensen, 2012). Although these methods mitigate integral windup, the trade-off is typically reduction in performance and/or increased system complexity with more tuning parameters.

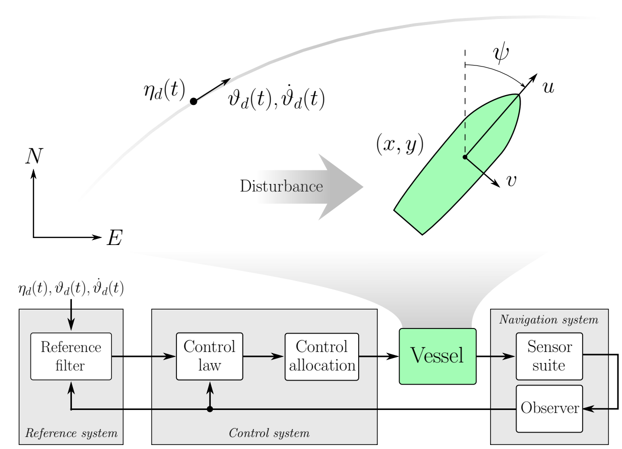

Fig. 1. Reference frames, desired trajectory, and signal flow in guidance, navigation, and control of marine vessels.

To deal with integral windup in LTI systems, Phelan (1977) proposed the pseudo-derivative feedback (PDF) control law. It is structurally similar to PID (Ohm, 1994) and a special case of the weighted reference PID by Åström and Hägglund (1995). The only difference from conventional PID is the lack of setpoint error in the proportional term. This vastly improves integral windup (and thereby reduces the need for the mentioned remedies). Although PDF is as simple as PID, and has demonstrated feasible experimental performance (Nikolic and Milivojevic, 1998; Setiawan et al., 2000), it has received little attention in marine applications. In the authors best knowledge, only Vahedipour and Bobis (1993) considers the method for autopilot design. Thus, the objective and contribution of this paper is to extend the PDF control law for LTI point

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stabilization to nonlinear tracking control for DP of marine vessels in presence of disturbances. Since PDF for LTI is not well know, an example is presented next.

Terminology and notation: In UGS, UGES, etc., stands G for Global, S for Stable, U for Uniform, and E for Exponential. LTI means linear time-invariant, and ISS means input-to-state-stable. The smallest and largest eigenvalues of a matrix $A \in \mathbb{R}^{n\times n}$ is denoted $\lambda_{\min}(A)$ and $\lambda_{\max}(A)$, respectively. $\mathbb{R}_{>0}$ denote positive real numbers and positive definite matrices.

1.1 Example

Consider the scalar second order system for which a point stabilization control law is to be designed,

$$m\ddot{q} + a\dot{q} = u + b \tag{1a}$$
$$\dot{b} = 0 \tag{1b}$$

where q, $\dot{q}$, $\ddot{q} \in \mathbb{R}$ is the position, velocity, and acceleration, respectively, $m, a \in \mathbb{R}_{>0}$ are known system parameters, and $b \in \mathbb{R}$ is a constant unknown bias. Full state feedback is assumed (i.e., $y := \begin{bmatrix} q & \dot{q} \end{bmatrix}^\top$), which enables PID and PDF control laws as,

$$u_{PID} = -k_p(q - q_d) - k_d(\dot{q} - \dot{q}_d) - k_i \int_0^t (q - q_d)\, dt \tag{2}$$

$$u_{PDF} = -l_p q - l_d \dot{q} - l_i \int_0^t (q - q_d)\, dt, \tag{3}$$

where $q_d \in \mathbb{R}$ is the setpoint, $\dot{q}_d \in \mathbb{R}$ is the desired velocity, $k_{p,d,i} \in \mathbb{R}$ are the PID gains, and $l_{p,d,i} \in \mathbb{R}$ are the PDF gains. The closed-loop transfer functions are thus,

$$q_{PID}(s) = \frac{(k_d s^2 + k_p s + k_i)q_d + bs}{ms^3 + (a + k_d)s^2 + k_p s + k_i} \tag{4}$$

$$q_{PDF}(s) = \frac{l_i q_d + bs}{ms^3 + (a + l_d)s^2 + l_p s + l_i}. \tag{5}$$

Notice that (4) and (5) have equal characteristic polynomial and disturbance rejection properties (provided equal tuning), but differ in the number of zeros.

Figure 2 shows a setpoint unit step of (1) comparing (2) to (3) with system parameters $m = 10$, $a = 2$, and $b = 2$. The PID is used with and without the following filter,

$$q_d'(s) = \frac{\omega_0^2 q_d}{s^2 + 2\zeta\omega_0 s + \omega_0^2}, \tag{6}$$

for smooth reference generation (replacing q_d, $\dot{q}_d$ with q_d', $\dot{q}_d'$ in (2)). (4) and (5) were designed with equal poles (s = -0.75, -0.25, and -0.25), and the PID reference filter was set to provide quick transient, but avoid overshoot ($\omega_0 = 0.21$ and $\zeta = 1$). The results show that the PDF obtains feasible performance which is comparable to the PID with a reference filter, but with the benefit of fewer tuning variables.

2. PROBLEM FORMULATION

The aim of this paper is to design a nonlinear tracking control law for DP using the PDF concept. As illustrated in Figure 1 the control objective is to track a desired time-varying North-East-Down (NED) trajectory parameterized by $\eta_d(t)$, $\vartheta_d(t)$, $\dot{\vartheta}_d(t) \in \mathbb{R}^3$. To achieve this the following control design model is applied,

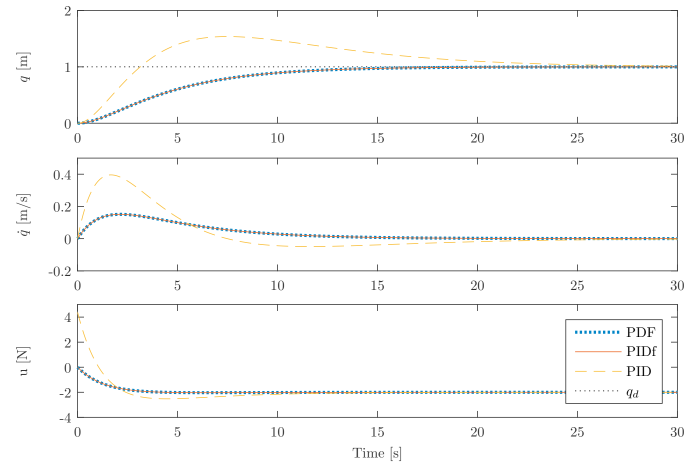

Fig. 2. Reference step simulation example results. PIDf denotes the use of a second order reference filter.

$$\dot{\eta} = R(\psi)\nu \tag{7a}$$
$$\dot{b} = 0 \tag{7b}$$
$$M\dot{\nu} + D\nu = \tau + MR^\top(\psi)b, \tag{7c}$$

where $\eta \in \mathbb{R}^3$ is the position and heading given in the NED frame, $R(\psi) \in \mathbb{R}^{3\times3}$ is the rotation matrix between the NED and vessel's body-fixed frame, $b \in \mathbb{R}^3$ is a bias state describing unmodeled dynamics and external loads, $M \in \mathbb{R}^{3\times3}_{>0}$ is the vessel inertia and added mass matrix, $\nu \in \mathbb{R}^3$ is the vessel's body-fixed linear and angular velocity, $D \in \mathbb{R}^{3\times3}_{>0}$ is a linear damping matrix, and $\tau \in \mathbb{R}^3$ is the control input. The design model is derived from the state-of-the-art models found in (Fossen, 2011; Sørensen, 2012) with one minor difference. The bias term is multiplied with the mass matrix M in (7c). This modification is reasonable as any external load may be described as mass times an acceleration. For the control design, ideal state feedback measurements of η and ν are assumed together with the following rotation matrix properties,

$$R(\psi)R(\psi)^\top = I \tag{8a}$$
$$\dot{R} = R(\psi)S(r), \tag{8b}$$

where $I \in \mathbb{R}^{3\times3}$ is the identity matrix, $S(r) \in \mathbb{R}^{3\times3}$ is a skew-symmetric matrix, and $r \in \mathbb{R}$ is the yaw-rate (for further details, see (Fossen, 2011)). For simplicity and readability, the arguments of $R(\psi)$ and $S(r)$ are dropped in the remainder of the paper.

For τ, the following nonlinear PDF tracking control law structure is proposed,

$$\tau = M(\tau_{FF} + \tau_{FB}) \tag{9a}$$
$$\tau_{FB} = R^\top(\xi - K_p\eta) - K_{D1}\nu + K_{D2}\nu_d \tag{9b}$$
$$\dot{\xi} = K_i(\eta_d - \eta) + \beta\vartheta_d, \tag{9c}$$

where $\tau_{FF} \in \mathbb{R}^3$ is a design feedforward term, $\beta \in \mathbb{R}^{3\times3}$ and $K_{p,D1,D2,i} \in \mathbb{R}^{3\times3}$ will be state-dependent design matrices, and $\xi \in \mathbb{R}^3$ is an integral action state. Similar to the example, the difference from conventional nonlinear PID control designs for marine vessels (as seen in e.g. (Sørensen, 2011)) is the lack of η_d in (9b), and inclusion of $\beta\vartheta_d$ in (9c). Hence, the problem treated in this paper is to design τ_{FF}, $K_{p,D1,D2,i}$, and β such that the vessel converges to, and tracks, the desired time-varying setpoint with feasible convergence trajectories.