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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.

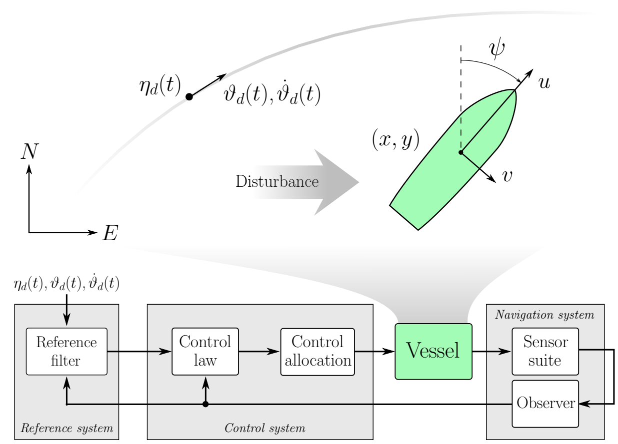

Fig. 1. Reference frames, desired trajectory, and signal flow in guidance, navigation, and control of marine vessels.

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,

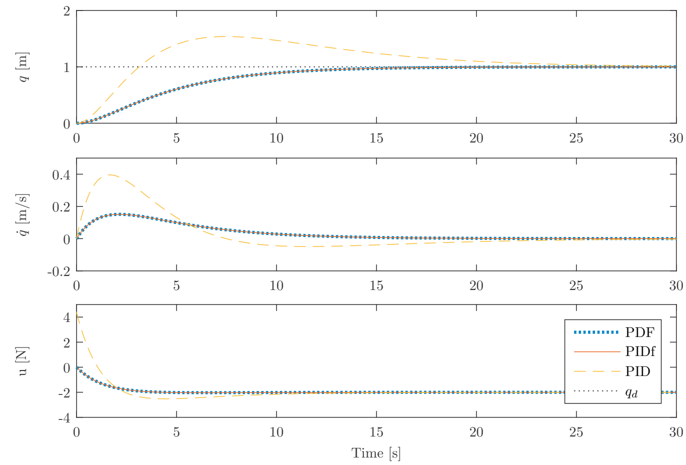

Fig. 2. Reference step simulation example results. PIDf denotes the use of a second order reference filter.

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

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.

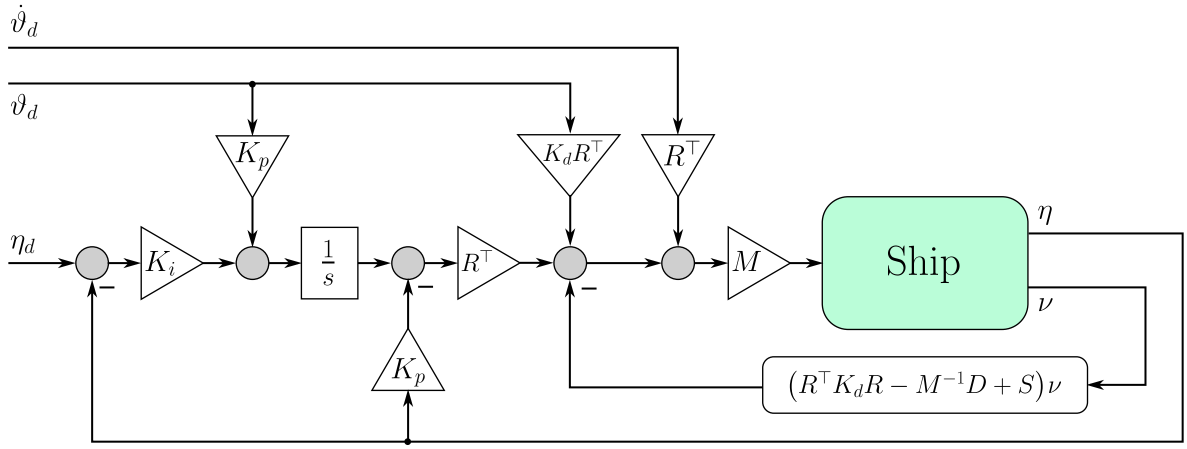

Fig. 3. Block diagram showing the nominal nonlinear tracking control law for DP.

3. CONTROL DESIGN

First, τ_{FF}, $K_{p,D1,D2,i}$, and β are derived to provide a nominal control law. Then, the results are extended to impose internal velocity constraints in (9c) such that feasible convergence trajectories are obtained. Finally, a set of tuning laws are proposed.

3.1 Nominal tracking design

To formalize the control law (9) the design model (7) is transformed to NED by $\vartheta := R\nu$ and $\vartheta_d := R\nu_d$, where $\nu_d \in \mathbb{R}^3$ is the body-fixed desired trajectory. This can be written as,

$$\dot{\eta} = \vartheta \tag{10a}$$
$$\dot{b} = 0 \tag{10b}$$
$$\dot{\vartheta} = RSR^\top\vartheta + RM^{-1}\left(\tau - DR^\top\vartheta + MR^\top b\right). \tag{10c}$$

Inserting (9) in (10c) gives the closed-loop dynamics,

$$\dot{\vartheta} = R\tau_{FF} + \xi - K_p\eta + b + RK_{D2}R^\top\vartheta_d \\ - R(K_{D1} + M^{-1}D - S)R^\top\vartheta. \tag{11}$$

From this it can be seen that choosing,

$$K_{D1} = R^\top K_d R - M^{-1}D + S \tag{12}$$
$$K_{D2} = R^\top K_d R, \tag{13}$$

where $K_d \in \mathbb{R}^{3\times3}$ is a gain matrix, the NED velocity dynamics become,

$$\dot{\vartheta} = R\tau_{FF} + \xi - K_p\eta + b - K_d(\vartheta - \vartheta_d). \tag{14}$$

To investigate the closed-loop stability properties and determine τ_{FF} and β, the following error variables are proposed,

$$e_1 = \eta_d - \eta \tag{15a}$$
$$e_2 = \vartheta_d - \vartheta \tag{15b}$$
$$e_3 = \xi - K_p\eta + b. \tag{15c}$$

Differentiating these give the closed-loop error dynamics,

$$\dot{e}_1 = e_2 \tag{16a}$$
$$\dot{e}_2 = \dot{\vartheta}_d - R\tau_{FF} - K_d\, e_2 - e_3 \tag{16b}$$
$$\dot{e}_3 = K_i e_1 + \beta\vartheta_d - K_p\vartheta. \tag{16c}$$

By choosing $\tau_{FF} = R^\top\dot{\vartheta}_d$ and $\beta = K_p$ the error dynamics become linear.

Theorem 1. The tracking control law (9) with

$$\tau_{FF} = R^\top\dot{\vartheta}_d \tag{17a}$$
$$K_{D1} = R^\top K_d R - M^{-1}D + S \tag{17b}$$
$$K_{D2} = R^\top K_d R \tag{17c}$$
$$\beta = K_p, \tag{17d}$$

render the equilibrium (e_1, e_2, $e_3 = 0$) of (16) UGES if the gains K_p, K_d, and K_i are designed to make the matrix

$$A = \begin{bmatrix} 0 & I & 0 \\ 0 & -K_d & -I \\ K_i & K_p & 0 \end{bmatrix}, \tag{18}$$

Hurwitz.

Proof. Letting $e = col(e_1, e_2, e_3)$ gives $\dot{e} = Ae$, which is UGES.

The integral windup problem is dealt with by the fact that the integral state ξ acts as an internal reference model (and integral action). This is possible as ξ is the only entry point of η_d (see Figure 3). Thus, there is no need for an external reference filter in order to avoid integral windup. A major benefit is that it reduces the overall control system complexity and mitigates the need for complex integral state handling logic. Since the control law (9), with (17), renders the closed-loop UGES, it is also ISS, and will be ideal for use in both a separation principle with an observer, and in more complex changing disturbance environments.

3.2 Constraining the convergence velocity

In DP it is beneficial to limit the velocity of the vessel as it converges to $\eta_d(t)$, $\vartheta_d(t)$, and $\dot{\vartheta}_d(t)$, so that it remains in the low velocity range. In conventional PID-like control designs this is typically achieved by limiting the velocity in the reference filter. In the proposed design, which has no reference filter, the convergence velocity may be impacted through tuning of K_i, K_p, and K_d, or by constraining $\dot{\xi}$. The second option is pursued as the tuning method is a trade-off that reduces the freedom of the response design. Since ϑ_d is given by the desired trajectory it should not be constrained in (9c) as that may lead to improper tracking. However, the proportional term $K_i(\eta_d - \eta)$ which governs the convergence velocity may. Thus, the following modification to (9c) is proposed,

$$\dot{\xi} = \mathrm{sat}(K_i e_1) + K_p \vartheta_d \tag{19}$$

where the saturation operator is defined by a maximum vector, denoted $\vartheta_{\max} \in \mathbb{R}^3_{>0}$. This is evaluated for the different elements in $K_i e_1$ so that $\mathrm{sat}(K_i e_1) \in [-\vartheta_{\max}\ \vartheta_{\max}]$.

Before proceeding to analyze the impact of this modification, we note that (9) with (17) and (19) can be written as,

$$\dot{e} = Ae + Bu \tag{20a}$$
$$y = Ce \tag{20b}$$
$$u = -\phi(y), \tag{20c}$$

where $B \in \mathbb{R}^{9\times 3} := [0\ 0\ I]^\top$, $u \in \mathbb{R}^3$, $C \in \mathbb{R}^{3\times 9} := [I\ 0\ 0]$, (A,B) is controllable, (A,C) is observable, and $\phi : \mathbb{R}^3 \to \mathbb{R}^3$ is a memoryless nonlinearity, locally Lipschitz in y.

Theorem 2. The tracking control law (9) with (17) and (19) render the system absolutely stable if (18) is Hurwitz, and

$$\gamma_1\gamma_2 < 1, \tag{21}$$

where $\gamma_2 := \lambda_{max}(K_i)$ and $\gamma_1 := \sup_{\omega\in\mathbb{R}} \|G(s)\|_2$, where $G(s) \in \mathbb{R}^{3\times 3}$ is the transfer function matrix of (20).

Proof. First note that $G(s)$ is Hurwitz since A is Hurwitz. The second condition of the circle criterion (Theorem 7.1 in (Khalil, 2001)), states that (20) is absolutely stable if $\phi \in [K_1,\ K_2]$, with $K = K_2 - K_1 = K^\top > 0$, and $Z(s) = [I + K_2 G(s)][I + K_1 G(s)]^{-1}$ strictly positive real (SPR).

The sector $[K_1,\ K_2]$ is established by noting that ϕ satisfies

$$\|\phi(y)\|_2 \le \gamma_2 \|y\|_2, \quad \forall y \in \mathbb{R}^3, \tag{22}$$

by choosing $\gamma_2 = \lambda_{max}(K_i)$. From this it follows that $K_1 = -\gamma_2 I$ and $K_2 = \gamma_2 I$, and $K^\top > 0$.

Lemma 6.1 in (Khalil, 2001) states that $Z(s)$ is SPR if $Z(s)$ is Hurwitz, $Z(j\omega) + Z^\top(j\omega) > 0\ \forall\omega \in \mathbb{R}$, and $Z(\infty) + Z^\top(\infty) > 0$. To show that these hold we define

$$\gamma_1 = \sup_{\omega\in\mathbb{R}} \|G(s)\|_2, \tag{23}$$

and note that γ_1 is finite as $G(s)$ is Hurwitz. The analysis showing $Z(s)$ SPR with (22) and (23) is identical to Example 7.1 in (Khalil, 2001), and therefore left out here. Then, the second condition of the multivariable circle criterion is satisfied, and we conclude that (20) is absolutely stable if $\gamma_1\gamma_2 < 1$.

3.3 Control synthesis

Since the nominal error dynamics (16) are linear, tuning laws based on the closed-loop transfer function can be proposed. By assuming that $K_{p,d,i}$ are diagonal, $\vartheta_d = 0$, $\dot{\vartheta}_d = 0$, and $b = 0$, it may be shown that each degree of freedom has the following transfer function,

$$h(s) = \frac{k_i}{s^3 + k_d s^2 + k_p s + k_i}, \tag{24}$$

where k_i, k_p, $k_d \in \mathbb{R}$ are diagonal terms of K_i, K_p, and K_d, respectively. To determine these, the following characteristic polynomial is proposed,

$$c(s) = (s+\alpha)(s^2 + 2\zeta\omega_0 + \omega_0^2) \tag{25a}$$
$$= s^3 + (2\zeta\omega_0 + \alpha)s^2 + (\omega_0^2 + 2\zeta\omega_0\alpha)s + \alpha\omega_0^2, \tag{25b}$$

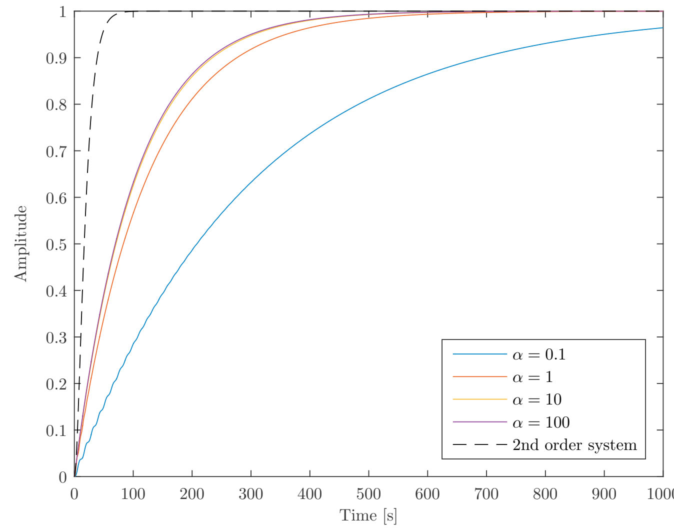

Fig. 4. Comparison of different α values for use in control parameter tuning.

where $\zeta \in \mathbb{R}$ is the damping factor, $\omega_0 \in \mathbb{R}$ is the natural frequency, and $\alpha \in \mathbb{R}$ is a filtering coefficient. From (24) and (25) it is found that,

$$k_d = 2\zeta\omega_0 + \alpha \tag{26a}$$
$$k_p = \omega_0^2 + 2\zeta\omega_0\alpha \tag{26b}$$
$$k_i = \alpha\omega_0^2. \tag{26c}$$

As the impact of α on the closed-loop dynamics is not well-known, Figure 4 shows a unit step comparison of (24) using a range of α values. For each value the control gains were calculated as in (26) using $\zeta = 1$ and $\omega_0 = 0.1$. It can be seen that α acts as an inverse first order lowpass filter time constant for the 2nd order system defined by ζ and ω_0. General tuning laws for the control law (9) with (17) are therefore proposed as,

$$K_p = diag\left(\begin{bmatrix} 2\zeta_x\omega_{0x} + \alpha_x \\ 2\zeta_y\omega_{0y} + \alpha_y \\ 2\zeta_\psi\omega_{0\psi} + \alpha_\psi \end{bmatrix}\right) \tag{27a}$$

$$K_d = diag\left(\begin{bmatrix} \omega_{0x}^2 + 2\zeta_x\omega_{0x}\alpha_x \\ \omega_{0y}^2 + 2\zeta_y\omega_{0y}\alpha_y \\ \omega_{0\psi}^2 + 2\zeta_\psi\omega_{0\psi}\alpha_\psi \end{bmatrix}\right) \tag{27b}$$

$$K_i = diag\left(\begin{bmatrix} \alpha_x\omega_{0x}^2 \\ \alpha_y\omega_{0y}^2 \\ \alpha_\psi\omega_{0\psi}^2 \end{bmatrix}\right), \tag{27c}$$

where the subscripts x, y, and ψ denote the parameter of the degree of freedom. It must be mentioned that other tuning methods may provide equal or better results as the above rely on assumptions of diagonal K_p, K_d, and K_i matrices and the specific characteristic equation given in (25). Yet, (27) provide an intuitive approach and give feasible results.

4. SIMULATION CASE STUDY

A simulation case study implementing (7) is conducted to verify the proposed PDF control design and evaluate its feasibility. The vessel in scope is the construction and intervention vessel for Arctic operations (CIVArctic), seen in Figure 5. It is a multi-purpose vessel capable of operating in open water on the Norwegian Continental Shelf and in first year in the High North (Berg, 2012). Table 1 gives its main particulars.

Fig. 5. The construction and intervention vessel for Arctic operations. Courtesy of (Berg, 2012).

Table 1. CIVArctic main parameters.

Parameter	Value
Length between perp.	109.3 m
Breadth at water line	24 m
Draught	6.5 m
Mass (normal load)	$11.85 \cdot 10^6$ kg

The simulation scenario is point stabilization followed by setpoint tracking subject to constant disturbance ($b = [25\ \ 0\ \ 0]^\top$). For the point stabilization we consider static setpoints given by $\eta_d(t) = \eta_d$ (implying $\vartheta_d(t), \dot{\vartheta}_d(t) = 0$), where η_d is changed twice with an interval of 250 seconds (at $t = 250s$, $500s$). At $t = 750$ seconds the vessel's control objective changes from point stabilization to setpoint tracking where the objective is to follow a linear trajectory parametrized by $\eta_d(t)$, $\vartheta_d(t)$, and $\dot{\vartheta}_d(t)$.

The nonlinear PDF design (9) using (17), with and without the convergence velocity constraints given in (19), is compared to the following nonlinear PID control law,

$$\tau_{PID} = M(\tau_{FF} + \tau_{FB}) \tag{28a}$$

$$\tau_{FB} = R^\top (\xi - K_p(\eta - \eta_d)) - K_{D1}\nu + K_{D2}\nu_d \tag{28b}$$

$$\dot{\xi} = K_i(\eta_d - \eta) \tag{28c}$$

where τ_{FF}, K_{D1}, and K_{D2} are given in (17). The error dynamics of (28) can be shown to be UGES by following the approach of Section 3.1. As both the PID and the PDF control laws have (24) as the characteristic equation, they are tuned equally with the method proposed in (27), using $\zeta = 1$, $\omega_0 = 0.06$, and $\alpha = 10$ (for all degrees of freedom).

To produce feasible transient PID performance, we propose the following general reference filter for setpoint tracking,

$$\ddot{\eta}_r = \dot{\vartheta}_d + \omega_{0r}^2\sigma + 2\zeta_r\omega_{0r}(\vartheta_d - \dot{\eta}_r) \tag{29a}$$

$$\ddot{\sigma} = \omega_{0\sigma}^2(\eta_d - \eta_r - \sigma) - 2\zeta_\sigma\omega_{0\sigma}\dot{\sigma}, \tag{29b}$$

where $\eta_r \in \mathbb{R}^3$ is the reference position and heading, $\omega_{0r}, \zeta_r, \omega_{0\sigma}, \zeta_\sigma \in \mathbb{R}_{>0}$ are positive scalars, and $\sigma \in \mathbb{R}^3$ is a reference acceleration state. For the simulation case this is applied with $\zeta_{r,\sigma} = 1$, $\omega_{0r} = 0.04$, and $\omega_{0r} = 0.5$. The initial condition of the PID reference position and the internal PDF reference state are both set to $\eta_r(0) = \xi(0) = \eta(0)$. For the PDF control law with velocity constraints, these are set to $\vartheta_{max} = [0.35\ \ 0.35\ \ 0.0175]^\top$.

Figures 6 and 7 show that all four closed-loop systems accomplish the control objective during both point stabilization and setpoint tracking, and that all are significantly affected at initialization due to the unknown environmental bias. As expected, the PID without a reference filter has less feasible transient performance during point stabilization setpoint changes compared to the others due to integral windup. For setpoint tracking (initialized at the vessel position) there is no difference in performance.

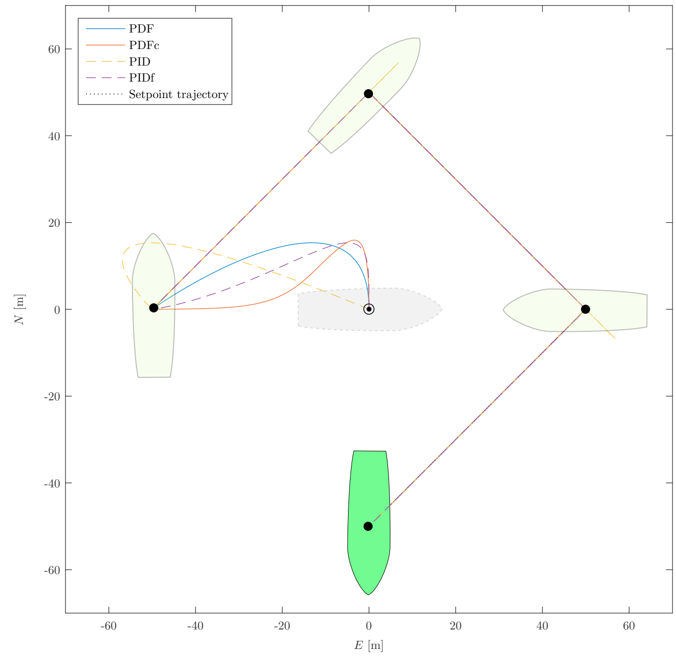

Fig. 6. The position trajectories of the control laws compared to the setpoints ans setpoint trajectory. PDFc denotes velocity constraint and PIDf denotes use of reference filter.

Note that the PDF velocity constraints only affect the transient convergence velocity, and not the total motion. This can be seen in Figure 7 where the limitations are respected during point stabilization as the resulting velocity is solely due to convergence. During setpoint tracking the total motion is mostly a result of the setpoint motion which is unaffected by the convergence limitations. Overall, the results indicate that the extension of the PDF concept to the nonlinear DP tracking problem is valid and that performance comparable to nonlinear PID control laws using a reference filter can be achieved.

5. DISCUSSION AND CONCLUSIONS

The main implications of the presented design are:

- Reduced number of tuning variables and implementation complexity.
- Ease of constraining the convergence velocity.

The reduced control system implementation complexity comes from the fact that the PDF control do not require a reference filter to achieve feasible convergence transients (as it mitigates integral windup). This simplifies synthesis and tuning and allows for designing highly reactive system responses without special attention to the integral action dynamics. Especially in harsh environment applications which includes effects such as wave trains, ship-ice interaction effects, ship-to-ship interaction effects, current surges,

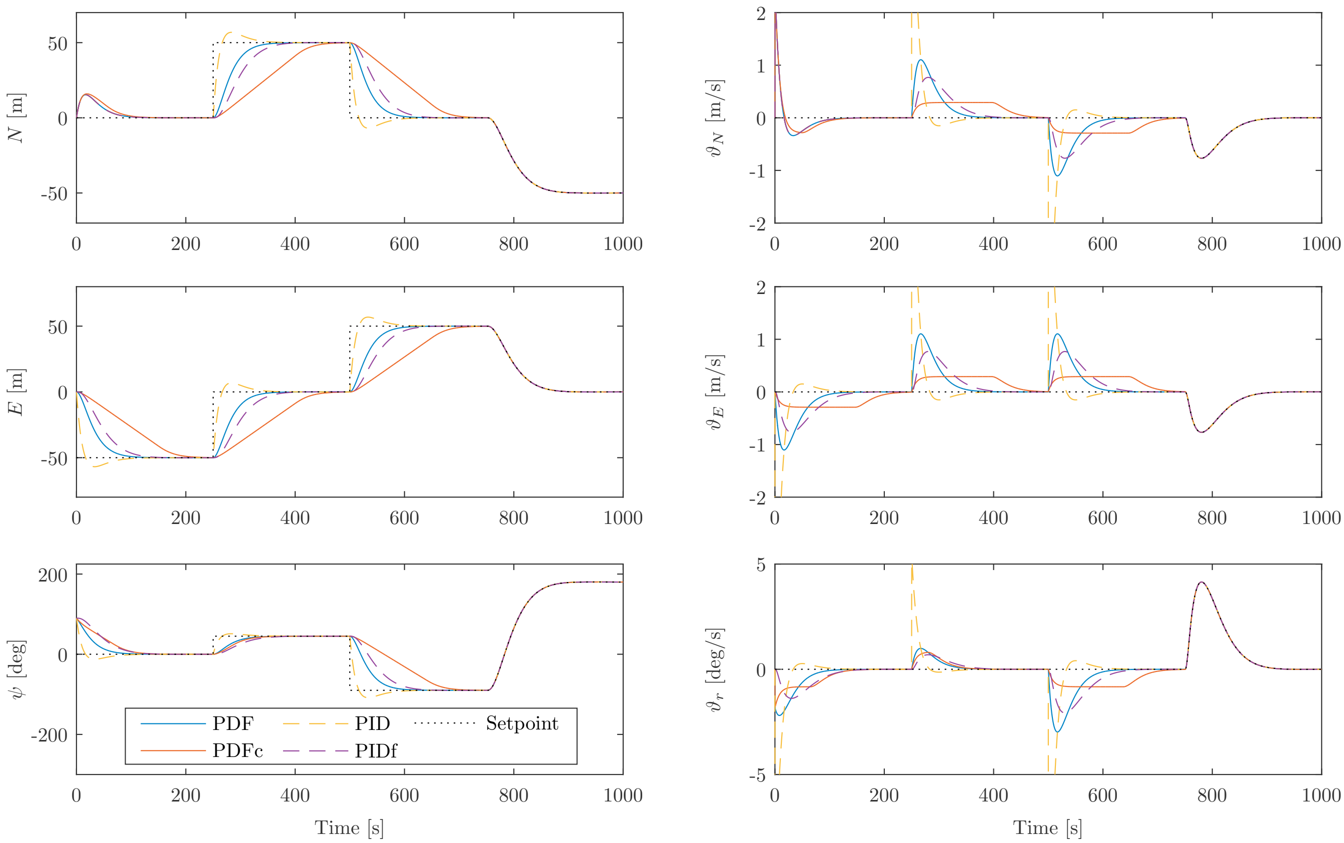

Fig. 7. Simulation case study results. The left column shows position and heading. The right column shows the linear velocity and angular rate. All signals are presented in the NED frame.

and effects from operations with heavy equipment in the sea or at the sea floor this can be of particular importance.

This paper has presented a robust tracking control law for DP of marine vessels that mitigates the integral windup problem often encountered in conventional PID-like designs. It is achieved by a subtle change in the control law feedback structure that allows the integral state to act as a reference point (and integral action). The proposed control law was analyzed and found to have uniform global exponential stability with respect to its error variables when subject to constant disturbance. Further, a method to constrain the convergence velocity was proposed and shown to render the error system absolutely stable. Together these mitigate the need for an explicit reference filter. A simulation case study verified the findings.

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