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Comparing Combinations of Linear and Nonlinear Feedback Terms for Motion Control of Marine Surface Vessels

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Abstract: Nonlinear control algorithms are often designed with linear feedback terms. Such linear feedback typically gives rise to nice exponential stability properties, but are not physically realistic since all actuators have magnitude constraints. One way to address such constraints can be to introduce nonlinear feedback terms. Hence, this paper investigates combinations of linear and nonlinear feedback terms for pose and velocity control of marine surface vessels. Three cascaded controllers are developed and compared through three simulation scenarios and one model-scale experiment. The comparisons are made using performance metrics which consider both control accuracy and energy use.

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1. INTRODUCTION

Automatic motion control of marine surface vessels has been a research topic since the early 20th century. In recent years, the research has expanded from control of manned vessels to also include unmanned vessels. However, many motion control algorithms found in the literature do not inherently consider physical saturation constraints for the actuators. For example, the nonlinear control algorithms in (Fossen and Strand, 1999),(Fossen, 2000), (Refsnes et al., 2008), (Fossen, 2011) and (Chen et al., 2013) are all designed with linear feedback terms.

This paper therefore investigates combinations of linear and nonlinear feedback terms for pose and velocity control of marine surface vessels. In particular, the nonlinear feedback terms are developed based on constant bearing (CB) guidance principles, inspired by the guided dynamic positioning approach originally suggested in (Breivik et al., 2006). Further inspiration has been found in (Breivik and Fossen, 2007) on the concept of guided motion control, as well as in (Breivik and Fossen, 2009). Also, the concept of CB guided motion control was employed in (Breivik and Loberg, 2011) for a virtual target-based underway docking control system, achieving docking of an unmanned surface vehicle with a mother ship moving in transit at sea. Similarly, a CB guided heading controller was designed in (Skejic et al., 2011) in order to maneuver a ship around a floating object in deep and calm water under the influence of a uniform current.

Specifically, three cascaded controllers are developed in the paper, where the feedback connection between pose and velocity which is traditionally found in backstepping control design has been removed. The controllers respectively employ linear feedback for both the pose and velocity control errors (LP-LV), nonlinear feedback for the pose control error and linear feedback for the velocity control error (NP-LV), as well as nonlinear feedback for both the pose and velocity control errors (NP-NV). The performance of the controllers are compared through three simulation scenarios and one model-scale experiment, where the comparisons are made using performance metrics which consider both control accuracy and energy use.

The structure of the paper is as follows: A mathematical vessel model and assumptions are presented in Section 2; Section 3 presents the design of three different cascaded control laws inspired by backstepping and CB guidance; Section 4 includes simulation results, experimental results and a performance evaluation; while Section 5 concludes the paper.

2. MARINE SURFACE VESSEL MODEL

The motion of a surface vessel can be represented by the pose vector $\boldsymbol{\eta} = [x, y, \psi]^\top \in \mathbb{R}^2 \times \mathbb{S}$ and the velocity vector $\boldsymbol{\nu} = [u, v, r]^\top \in \mathbb{R}^3$, where $\mathbb{S} \in [-\pi, \pi]$. Here, (x, y) represents the Cartesian position in the local earth-fixed reference frame, ψ is the yaw angle, (u, v) represents the body-fixed linear velocities and r is the yaw rate. The 3 degrees-of-freedom dynamics of a surface vessel can then be stated as (Fossen, 2011):

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

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{D}(\boldsymbol{\nu})\boldsymbol{\nu} = \boldsymbol{\tau}, \tag{2}$$

where

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

is a rotation matrix $\mathbf{R} \in SO(3)$, and where $\mathbf{M}$, $\boldsymbol{C(\nu)}$, $\boldsymbol{D(\nu)}$ and $\boldsymbol{\tau}$ represent the inertia matrix, Coriolis and centripetal matrix, damping matrix and control input vector, respectively. Here, the system matrices are assumed to satisfy the properties $\mathbf{M} = \mathbf{M}^\top > 0$, $\mathbf{C}(\boldsymbol{\nu}) = -\mathbf{C}(\boldsymbol{\nu})^\top$ and $\mathbf{D}(\boldsymbol{\nu}) > 0$.

Since this paper focuses on fundamental motion control aspects, it is assumed that both the pose vector $\boldsymbol{\eta}$ and velocity vector $\boldsymbol{\nu}$ can be measured, and that no disturbances and uncertainties are affecting the system. Such assumptions will be relaxed and investigated elsewhere.

3. FEEDBACK CONTROL DESIGN

The control objective is to make $\tilde{\boldsymbol{\eta}}(t) \triangleq \boldsymbol{\eta}(t) - \boldsymbol{\eta}_t(t) \to \mathbf{0}$ as $t \to \infty$, where $\boldsymbol{\eta}_t(t) = [x_t(t), y_t(t), \psi_t(t)]^\top \in \mathbb{R}^2 \times \mathbb{S}$ represents the pose associated with a target point which is $\mathcal{C}^2$ and bounded. The motion of the target is typically defined by a human or generated by a guidance system.

The control design is divided into two stages, including definition of new state variables and deriving the control laws through control Lyapunov functions (CLFs). The design is similar to the backstepping method, which has been applied in e.g. (Fossen and Strand, 1999) and (Sørensen and Breivik, 2015), but omits the coupling between the pose and velocity control loops, resulting in a cascade system. This cascade system represents a classical inner-outer loop guidance and control structure, where the outer loop handles the kinematics and the inner loop handles the vessel kinetics. The total system can then be analysed by cascade theory (Lamnabhi-Lagarrigue et al., 2005).

In particular, it is desirable to investigate the effect of using nonlinear feedback terms, inspired by CB guidance (Breivik and Fossen, 2009), compared to standard linear feedback terms. Consequently, we investigate three combinations of linear and nonlinear feedback terms.

For notational simplicity, the time t is omitted in the rest of this section.

3.1 Linear Pose and Velocity Feedbacks

Start by defining the error variables $\mathbf{z}_1$ and $\mathbf{z}_2$:

$$\mathbf{z}_1 \triangleq \mathbf{R}^\top(\psi)(\boldsymbol{\eta} - \boldsymbol{\eta}_t) \tag{4}$$

$$\mathbf{z}_2 \triangleq \boldsymbol{\nu} - \boldsymbol{\alpha}, \tag{5}$$

where $\boldsymbol{\alpha} \in \mathbb{R}^3$ is a vector of stabilising functions, which can be interpreted as a desired velocity and which is to be designed later.

Kinematic Control

Choosing the positive definite CLF

$$V_1 \triangleq \frac{1}{2}\mathbf{z}_1^\top \mathbf{z}_1, \tag{6}$$

the derivative of V_1 with respect to time along the $\mathbf{z}_1$-dynamics gives

$$\begin{aligned} \dot{V}_1 &= \mathbf{z}_1^\top \dot{\mathbf{z}}_1 \\ &= \mathbf{z}_1^\top (\mathbf{S}(r)^\top \mathbf{R}^\top(\psi)(\boldsymbol{\eta} - \boldsymbol{\eta}_t) + \mathbf{R}^\top(\psi)(\dot{\boldsymbol{\eta}} - \dot{\boldsymbol{\eta}}_t)) \\ &= \mathbf{z}_1^\top (\mathbf{S}(r)^\top \mathbf{z}_1 + \mathbf{R}^\top(\psi)(\dot{\boldsymbol{\eta}} - \dot{\boldsymbol{\eta}}_t)), \end{aligned} \tag{7}$$

where

$$\mathbf{S}(r) = \begin{bmatrix} 0 & -r & 0 \\ r & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{8}$$

is a skew-symmetric matrix satisfying $\mathbf{z}_1^\top \mathbf{S}(r)^\top \mathbf{z}_1 = 0$, which gives

$$\dot{V}_1 = \mathbf{z}_1^\top (\boldsymbol{\nu} - \mathbf{R}^\top(\psi)\dot{\boldsymbol{\eta}}_t). \tag{9}$$

Using (5), the CLF becomes

$$\begin{aligned} \dot{V}_1 &= \mathbf{z}_1^\top (\mathbf{z}_2 + \boldsymbol{\alpha} - \mathbf{R}^\top(\psi)\dot{\boldsymbol{\eta}}_t) \\ &= \mathbf{z}_1^\top \mathbf{z}_2 + \mathbf{z}_1^\top (\boldsymbol{\alpha} - \mathbf{R}^\top(\psi)\dot{\boldsymbol{\eta}}_t), \end{aligned} \tag{10}$$

where the stabilising function can be chosen as

$$\boldsymbol{\alpha} = \mathbf{R}^\top(\psi)\dot{\boldsymbol{\eta}}_t - \mathbf{K}_1 \mathbf{z}_1 \tag{11}$$

with $\mathbf{K}_1 > 0$, which results in

$$\dot{V}_1 = -\mathbf{z}_1^\top \mathbf{K}_1 \mathbf{z}_1 + \mathbf{z}_1^\top \mathbf{z}_2. \tag{12}$$

It can be concluded that the origin of $\mathbf{z}_1$ is uniformly globally exponentially stable (UGES) when seeing $\mathbf{z}_2$ as an input with $\mathbf{z}_2 = \mathbf{0}$. Consequently, it can be concluded by Lemma 4.6 from (Khalil, 2002) that the subsystem

$$\dot{\mathbf{z}}_1 = \mathbf{S}(r)^\top \mathbf{z}_1 - \mathbf{K}_1 \mathbf{z}_1 + \mathbf{z}_2 \tag{13}$$

is input-to-state stable (ISS). Note that (12) shows that $\mathbf{S}(r)$ in (13) does not affect the ISS property.

Kinetic Control

The $\mathbf{z}_2$-dynamics can be written as

$$\begin{aligned} \mathbf{M}\dot{\mathbf{z}}_2 =& \mathbf{M}(\dot{\boldsymbol{\nu}} - \dot{\boldsymbol{\alpha}}) \\ =& \boldsymbol{\tau} - \mathbf{C}(\boldsymbol{\nu})\boldsymbol{\nu} - \mathbf{D}(\boldsymbol{\nu})\boldsymbol{\nu} - \mathbf{M}\dot{\boldsymbol{\alpha}}, \end{aligned} \tag{14}$$

where the time derivative of (11) becomes

$$\dot{\boldsymbol{\alpha}} = \mathbf{R}^\top(\psi)\ddot{\boldsymbol{\eta}}_t + \mathbf{S}(r)^\top \mathbf{R}^\top(\psi)\dot{\boldsymbol{\eta}}_t - \mathbf{K}_1 \dot{\mathbf{z}}_1 \tag{15}$$

where $\boldsymbol{\eta}_t$ is the pose of the target point and $\dot{\mathbf{z}}_1$ given by (13). The CLF for $\mathbf{z}_2$ is then defined as

$$V_2 \triangleq \frac{1}{2}\mathbf{z}_2^\top \mathbf{M}\mathbf{z}_2. \tag{16}$$

Simplifying $\mathbf{C}(\boldsymbol{\nu}) = \mathbf{C}$, $\mathbf{D}(\boldsymbol{\nu}) = \mathbf{D}$, $\mathbf{R}(\psi) = \mathbf{R}$ and $\mathbf{S}(r) = \mathbf{S}$ for notational brevity, the derivative of (16) becomes

$$\begin{aligned} \dot{V}_2 =& \mathbf{z}_2^\top \mathbf{M}\dot{\mathbf{z}}_2 \\ =& \mathbf{z}_2^\top (\boldsymbol{\tau} - \mathbf{C}\boldsymbol{\nu} - \mathbf{D}\boldsymbol{\nu} - \mathbf{M}\dot{\boldsymbol{\alpha}}). \end{aligned} \tag{17}$$

The control input can be chosen as

$$\boldsymbol{\tau} = \mathbf{M}\dot{\boldsymbol{\alpha}} + \mathbf{C}\boldsymbol{\nu} + \mathbf{D}\boldsymbol{\nu} - \mathbf{K}_2 \mathbf{z}_2, \tag{18}$$

where $\mathbf{K}_2 > 0$, which results in

$$\dot{V}_2 = -\mathbf{z}_2^\top \mathbf{K}_2 \mathbf{z}_2 < 0, \tag{19}$$

which makes the origin of the $\mathbf{z}_2$-dynamics

$$\dot{\mathbf{z}}_2 = -\mathbf{M}^{-1}\mathbf{K}_2 \mathbf{z}_2 \tag{20}$$

UGES.

It should be noted that it is possible to choose $\boldsymbol{\tau}$ in (18) as e.g.

$$\boldsymbol{\tau} = \mathbf{M}\dot{\boldsymbol{\alpha}} + \mathbf{C}\boldsymbol{\alpha} + \mathbf{D}\boldsymbol{\alpha} - \mathbf{K}_2 \mathbf{z}_2, \tag{21}$$

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