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Short communication

Two-time scale path following of underactuated marine surface vessels: Design and stability analysis using singular perturbation methods

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ABSTRACT

The paper aims to develop a novel path following control law for nonlinear vessel models in two-time scales. For the 4-DOF path following model, we explore that the guidance dynamics are much slower than the ship motion dynamics. Based on such characteristic, a singular perturbation method is used to decompose the full system into two-time-scale subsystems. The two-time-scale structure allows independent analysis of dynamics in each time scale. Separate control strategies for the quasi-steady-state subsystem and the boundary layer subsystem are designed to stabilize the full system, yielding a rudder angle control law which is compact and uncomplicated to implement in practice. Singular perturbation methods are utilized to provide mathematical expressions for the upper bound of the singularly perturbed parameter and establish the exponential stability of the full system. The paper proves that the control law is robust in the presence of bounded perturbations and unmodeled dynamics, resulting states converge into an invariant set arbitrarily closed to the origin. Simulation results show the effectiveness and robustness of the proposed method for path following. The primary benefit of the proposed method is the simplicity of implementation.

1. Introduction

Over the past decade, trajectory tracking and path following issues of marine surface vessels have been priority areas for the marine control community. The path following issue is the task of following a predefined path independent of time. Such task is often represented as a nonlinear system with inherent instability and underactuated properties, making it a challenge.

Conventional vessels are usually controlled by main propellers and rudders. Mathematically, this class of systems are underactuated systems. A frequently used method for path following is the waypoint guidance, such as line-of-sight (LOS) guidance laws (Fossen and Pettersen, 2014; Fossen et al., 2015; Oh and Sun, 2010). The selected waypoints are used for generation of a path for vessels to follow. In most way-point guidance and control systems, both guidance dynamics and ship motion dynamics have inherent nonlinearities. Historically, some conventional linear control techniques have been adopted for marine surface vessels to obtain reasonable responses, such as PID-type controller (Källström, 2000), LQR controller (Holzhüter, 1997) and linear MPC approach (Oh and Sun, 2010). Domains of attraction are typically small for controllers based on linearized system dynamics, and they are usually sensitive to perturbations. The improvement of technology and evolutions of the marine industry have increased performance requirements of ship control systems. Consequently, linear control algorithms are insufficient to deal with them, and inherent nonlinearities are studied rather than linear approximations. In the area of ocean engineering, numerous nonlinear control methods have been studied to cope with underactuated nonlinear systems, including backstepping control techniques (Li et al., 2009; Do et al., 2002), adaptive control (Fossen et al., 2015; Hespanha et al., 2007; Fossen and Lekkas, 2016), cascade control methods (Fossen and Pettersen, 2014; Lefeber et al., 2003), sampled-data control theory (Katayama and Aoki, 2014), sliding mode control (Ashrafiuon et al., 2008) and neural networks control (Zhang et al., 2015). They have offered new tools and promising solutions to deal with ship motion control. However, nonlinear control techniques usually yield relatively complicated control laws which are arduous to implement in practice. Besides, these methods cannot

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handle a time-scale separation caused by different rates of numerous variables.

For guidance dynamics and ship motion dynamics, there is the simultaneous occurrence of slow and fast phenomena, which arouses multi-time scales. Therefore, hierarchical control is a suitable method in practical ocean engineering. Singular perturbation methods, which have the ability to separate and analyze multi-time scales, have been successfully used in nonlinear under-actuated control in the last decade (Lee et al., 2015; Esteban et al., 2013). Singular perturbation methods simplify the controller design procedure. However, few works of singular perturbation and time scale separation methods have been explored in ship control community, which is mainly due to relatively poor rudder effects and simple control objectives for marine surface vessels (Ren et al., 2014). To our knowledge, while singular perturbation methods have been reported for ship motion applications, studies on path following control of marine surface vessels in multi-time-scale structure have hardly been seen in open literature.

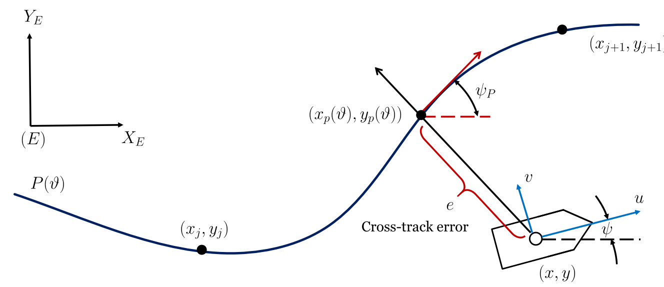
The background of singular perturbation methods could be found in Khalil (2002) and Kokotovic et al. (1999). There are some literature of singularly perturbed methods that are applied to the aerospace industry (Kokotovic et al., 1999; Esteban et al., 2015; Esteban and Rivas, 2012; Bertrand et al., 2011; Naidu and Calise, 2001). Singular perturbation systems can be stabilized in multi-time scales separately, simplifying the control design of high-order systems. In Bertrand et al. (2011), separate translational dynamics (the slow time-scale) and orientation dynamics (the fast time-scale). Motivated by Bertrand et al. (2011) and some recent developments in ship motion control, we find that there is a similar time-scale separation phenomenon between guidance dynamics and ship motion dynamics for path following of marine surface vessels. Our focus is developing a nonlinear path following controller for marine surface vessels, which should be easy to implement in practice and handle a time-scale separation.

In this paper, we present the design procedure and stability analysis of path following of marine surface vessels using singular perturbation methods. A 2-DOF waypoint guidance law and a 3-DOF ship motion model are considered. The full dynamical model is formulated as a 4-DOF model with the assumption of constant surge velocity (Li et al., 2009). It is observed that the guidance dynamics and ship motion dynamics are presented in two-time-scale subsystems. A singularly perturbed model of the full dynamics is presented by comparison of bounds and speeds of state variables. We design the composite rudder angle controller in the fast subsystem and the slow subsystem respectively. The robust performance of the proposed nonlinear controller is studied in the presence of bounded perturbations and unmodeled dynamics. A unique feature of this work is that the time scale decomposition approach simplifies the control design procedure of path following.

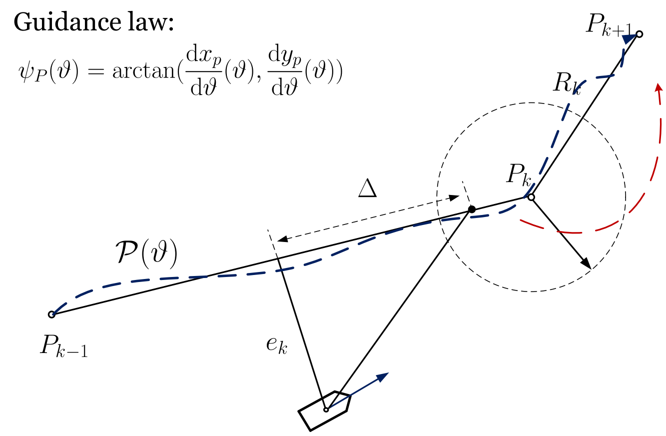
The structure of this paper is as follows. Section 2 introduces some preliminaries, including the way-point guidance law, kinematic equations and singular perturbation methods. In Section 3.1, the multi-time decomposition is analyzed. Section 3.2 gives the singularly perturbed model of the path following of marine surface vessels in calm water. Controller design and stability analysis are also presented in this section. The robustness analysis is given with bounded perturbations and unmodeled dynamics in Section 3.3. Simulations are shown in Section 4 and Section 5 concludes.

2. Preliminaries

This section describes the general formulation of the guidance and motion dynamics of marine surface vessels. Besides, the main results of singular perturbation methods are introduced.



(a) Illustration of the guidance geometry



(b) LOS guidance for a straight line

Fig. 1. (a) Illustration of the guidance geometry. (b) LOS guidance for a straight line.

2.1. Guidance law and kinematic equations

The task of path following is to track a given path independent of time. Let ϑ denote the path variable and $\vartheta > 0$. For marine surface vessels, a predefined path is described as a two-dimensional geometric curve $\mathcal{P}(\vartheta) \in \mathbb{R}^2$ which is parameterized by the continuous variable ϑ (Fossen, 2011). The two-dimensional C^1 parameterized path $\mathcal{P}(\vartheta) = (x_p(\vartheta), y_p(\vartheta))$ goes through a set of waypoints $\left(x_j, y_j\right)$ ($j = 1, 2, \ldots, N$) as Fig. 1a, which shows the Serret–Frenet (SF) frame used for path following control. The point $(x(\vartheta), y(\vartheta))$, which is located at the closest point on the curve $\mathcal{P}(\vartheta)$ from the centroid position of the vessel (x,y), is the origin of the Serret–Frenet frame. The cross-track error $e(t)$ represents the error dynamics. ψ_P is the tangential direction of the given trajectory and $\psi_P\left(\vartheta\right) = \arctan\left(\frac{dx_p}{d\vartheta}\left(\vartheta\right), \frac{dy_p}{d\vartheta}\left(\vartheta\right)\right)$. $\psi(t)$ denotes the heading angle of the vessel in the earth frame, and $\tilde{\psi} = \psi - \psi_P$ is the heading error. Skjetne and Fossen develop the Serret–Frenet dynamic equations as follows (Skjetne and Fossen, 2001):

$$\dot{\tilde{\psi}} = \frac{\kappa}{1 - e\kappa}(u \sin \tilde{\psi} - v \cos \tilde{\psi}) + r \tag{1}$$

$$\dot{e} = u \sin \tilde{\psi} + v \cos \tilde{\psi} \tag{2}$$

where κ is referred as the curvature of $\mathcal{P}(\vartheta)$ at the point $(x_P(\vartheta), y_P(\vartheta))$. For most path following control of marine surface vessels, the given curve could be approximated as a way-point path $(\ldots, P_{k-1}, P_k, P_{k+1}, \ldots)$ as Fig. 1b (Oh and Sun, 2010). When the vessel is within a circle of the current way-point P_k (the radius $r = R_k$), the guidance law will switch to the next way-point P_{k+1}. The curvature κ of a straight line is zero. Therefore (1) can be