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Three-dimensional trajectory tracking for underactuated AUVs with bio-inspired velocity regulation

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Abstract

This paper attempts to address the motion parameter skip problem associated with three-dimensional trajectory tracking of an underactuated Autonomous Underwater Vehicle (AUV) using backstepping-based control, due to the unsmoothness of tracking trajectory. Through kinematics concepts, a three-dimensional dynamic velocity regulation controller is derived. This controller makes use of the surge and angular velocity errors with bio-inspired models and backstepping techniques. It overcomes the frequently occurring problem of parameter skip at inflection point existing in backstepping tracking control method and increases system robustness. Moreover, the proposed method can effectively avoid the singularity problem in backstepping control of virtual velocity error. The control system is proved to be uniformly ultimately bounded using Lyapunov stability theory. Simulation results illustrate the effectiveness and efficiency of the developed controller, which can realize accurate three-dimensional trajectory tracking for an underactuated AUV with constant external disturbances.

Keywords: Dynamic velocity regulation; Bio-inspired model; Backstepping; Underactuated AUV; Three-dimensional trajectory tracking

1. Introduction

Precise three-dimensional trajectory tracking of Autonomous Underwater Vehicles (AUVs) is an important technical prerequisite for marine resources development, scientific investigation, and offshore defense (Thor I. Fossen, 2011; Do Wan Kim, 2015; Yu-shan Sun et al., 2016). However, unmanned AUVs are usually underactuated, highly coupled, and nonlinear (K.D. Do, 2015; Fossen. T. I et al., 2015). The AUV studied in this paper lacks actuators in the sway and heave directions, and thus can be classified as a typical underactuated system. With external disturbances, as well as time and space requirements, three-dimensional trajectory tracking of AUV is further complicated.

Currently, several methods have been proposed to track underactuated AUVs, such as sliding mode control (Taha Elmokadem et al., 2016; Zheping Yan et al., 2015; Jia Heming et al., 2012a,b), neural network control (Zhou et al., 2013), and backstepping technique (F.Y. Bi et al., 2010; Jia He-ming et al., 2012a,b; Wang Hong-Jian et al., 2015; Aguiar, A. and Joao, P. 2007; Xu et al., 2014). These control methods have their own advantages and limitations. Taha Elmokadem et al. (2016) combined a hyperbolic function with sliding mode control, based on which the speed jump problem was solved and planar trajectory tracking for an underactuated AUV was achieved. In order to deal with the disturbances caused by model parameters and unknown external environment, Zheping Yan et al. (2015) proposed a method to realize global finite-time planar trajectory tracking for an underactuated vehicle. These two methods above are still limited to control only in the horizontal plane, without taking account of

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three-dimensional trajectory tracking. To achieve three-dimensional trajectory tracking control, Jia He-ming et al. (2012a,b) used a nonlinear iteration-based sliding mode to lower the chattering of the hydroplane and reduce the over-shoot. However, these methods still have difficulties in fundamentally solving the issue of chatting associated with sliding mode control. Zhou, Jiajia et al. (2013) proposed three neural network controllers to estimate unknown parameters and external disturbances, where a desired spatial path was tracked successfully for an AUV. However, learning of the neural network was indeed time consuming.

In order to tackle the speed jump problem of backstepping technique, F.Y. Bi et al. (2010) simplified the mid-calculation process in traditional backstepping method using virtual velocity errors, making AUV tracking control possible in a horizontal plane. Jia He-ming et al. (2012a,b) proposed an adaptive backstepping approach to suppress disturbances from ocean current and achieved three-dimensional path tracking control. Wang Hong-Jian et al. (2015) developed a filtered backstepping method to simplify the process of obtaining derivatives and filter out high-frequency noise in three-dimensional path-following control. However, the effects of time-varying trajectory on vehicle speed and attitude were not considered in these studies.

To overcome the uncertainty of model parameters, Aguiar, A. and Joao, P. (2007) proposed an adaptive switching control monitoring strategy, which guaranteed the system errors to be globally bounded. To avoid singularity occurrence in the line-of-sight backstepping method, Xu et al. (2014) defined multiple virtual speed error variables to help achieve three-dimensional trajectory tracking. However, the way it used to deal with singularity would degrade the control performance of the system; furthermore, the trajectory inflection point issue was not considered. K.D. Do (2015) designed a robust adaptive controller, which eliminated external disturbances and succeeded in planar trajectory tracking. In Simon. X. Yang and T. Hu (2002), Simon X. Yang et al. (2012), Chang-Zhong Pan et al. (2013), a bio-inspired model combined with backstepping was developed for mobile robots and surface ships. Because the dynamics models of these vehicles were relatively simple, their controller designs were also fairly easy to implement. Bing Sun et al. (2014a) and Bing Sun et al (2014b) successfully applied the bio-inspired model to a fully actuated manned submarine vehicle and an unmanned underwater vehicle, respectively. This method only generated smooth and filtered signals in the kinematic model without considering the dynamic model.

In this paper, a method of integrating bio-inspired models and backstepping technique is adopted to carry out three-dimensional trajectory tracking control for an underactuated AUV. The rest of this paper is organized as follows. Section 2 describes the problems of AUV modeling and coordinate transformation. Three assumptions and three bio-inspired models are proposed to support the control objects of three-dimensional trajectory tracking. Section 3 develops a three-dimensional trajectory tracking controller for underactuated AUVs with velocity regulation using Lyapunov theory and backstepping technique. Section 4 proves that the control system is uniformly ultimately bounded under constant external disturbances. Section 5 presents simulation process and discussion of the obtained results. Finally, the last section makes a summary of the three-dimensional trajectory tracking scheme and concludes its advantages.

2. Problem description

In this section, the three-dimensional kinematic and kinetic models for an underactuated AUV are established first. The conversion between earth-fixed coordinate and the body-fixed coordinate is also performed. Next, issues related to three-dimensional trajectory tracking control are addressed. The bio-inspired models used to regulate velocity error are then introduced.

2.1. Underactuated AUV modeling and coordinate transformation

This type of AUVs studied in the present work lacks sway and heave propellers. Therefore, it can be classified as a typical underactuated AUV. To better analyze the motion of AUV in the three-dimensional space, we define two coordinate systems as shown in Fig. 1E and B represent the earth-fixed coordinate system and the body-fixed coordinate system of the AUV, respectively.

The matrix-vectors of kinematic and kinetic models for AUV are:

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J}(\boldsymbol{\eta})\mathbf{v} \tag{1}$$

$$\boldsymbol{M}\dot{\mathbf{v}} = \boldsymbol{\tau} + \boldsymbol{\tau}_{\omega} - \boldsymbol{C}(\mathbf{v})\mathbf{v} - \boldsymbol{D}(\mathbf{v})\mathbf{v} - \mathbf{g}(\boldsymbol{\eta}) \tag{2}$$

where $\eta = [X_E, Y_E, Z_E, \theta, \psi]^{\mathrm{T}} \in \Re^5$ denotes the AUV's position and attitude vector in earth-fixed coordinate system; $J(\eta)$ is the transformation matrix between the earth-fixed coordinate system and the body-fixed coordinate system; M is inertia matrix, including added mass; $v = [u, v, w, q, r]^{\mathrm{T}} \in \Re^5$is

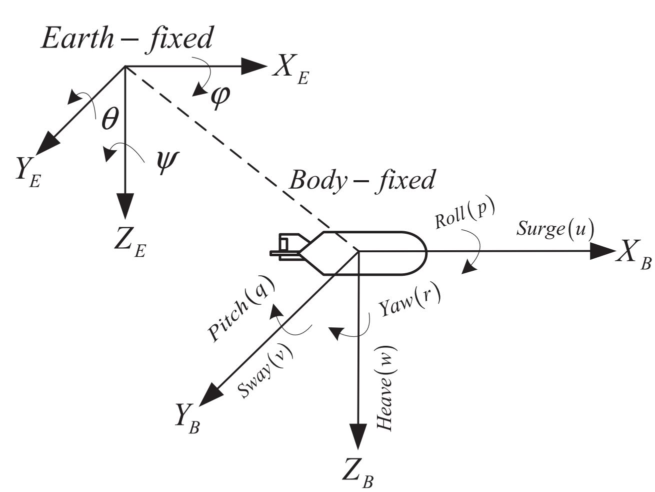

Fig. 1. AUV coordinate system.

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