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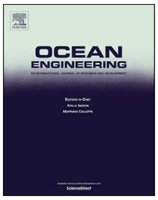

Nonlinear guidance and fuzzy control for three-dimensional path following of an underactuated autonomous underwater vehicle

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ABSTRACT

This paper proposes a simplified nonlinear fuzzy controller integrating an improved three-dimensional (3D) guidance law, in order to address the problem of path following for an underactuated autonomous underwater vehicle (AUV) exposed to unknown environmental disturbances. First, an improved 3D line-of-sight guidance law that makes full use of the essentially equivalent coordinate transformation is derived to transform 3D path following position errors into controlled guidance speeds, which also reduces the path following system form second-order to first-order. The side-slip angle and angle of attack are integrated into 3D guidance design to account for the underactuated configuration in sway and heave. Second, a nonlinear single-input fuzzy controller is designed to reduce computation complexity resulting from square rules in a double-input fuzzy controller, and to force the steerable speeds of an AUV to attain their guidance profiles. Subsequently, sensitivity analysis is adopted to suggest that the nonlinear fuzzy design with the convergent distribution and small slope for the single input have better robustness against unknown disturbances than the linear design. Finally, numerical examples with quantitative comparison are provided to illustrate the performance of the nonlinear single-input fuzzy controller for 3D path following of an underactuated AUV exposed to unknown environmental disturbances.

1. Introduction

Autonomous underwater vehicles (AUVs) are increasingly being used in the scientific, commercial, military, and policy sectors, such as underwater intervention (Zhang et al., 2015), monitoring and inspection (Xiang et al., 2010), target tracking (Shojaei and Dolatshahi, 2017), and sampling and patrolling (Zhang et al., 2007; Xiang et al., 2015a), etc. In order to accomplish diverse underwater tasks, it is desirable to automatically steer an AUV along a predefined path. Yet, most of AUVs equipped with two pairs of rudders and a stern propeller, such as REMUS 6000 and HUGIN 1000, cannot independently generate lateral and vertical control forces, which belong to a kind of underactuated systems with more degrees of freedom to be controlled than the number of independent control inputs and suffer from non-integrable second-order nonholonomic constraints (Yi et al., 2016; Xiang et al., 2016a). In addition, the AUV itself has the highly coupled dynamics and positive buoyancy (Zhu et al., 2017; Tanakitkorn et al., 2017), and it is persistently subjected to drift effects included by unpredictable environmental disturbances including the wind, waves and currents (Liang et al., 2017; Gao et al., 2016; Peng et al., 2015; Miao et al., 2017a). Hence, the motion control of an underactuated AUV is a difficult task and attracts the attention of numerous researchers worldwide (Xiang et al., 2017c).

The basic motion tasks of autonomous vehicles including mobile wheeled robots (MWRs), unmanned surface vehicles (USVs), remotely operated vehicles (ROVs) and AUVs are classified as trajectory tracking and path following (Do, 2016; Fossen et al., 2015; Wang et al., 2017a; Zhang et al., 2013; Chu et al., 2017b). In the trajectory tracking task, the vehicle must reach a specific point at a pre-assigned time instant. Hence, it inherently integrates space and time assignments into single assignment (Chu et al., 2017a; Qiao and Zhang, 2017; Wang et al., 2015, 2017b; Xiang et al., 2017d). While path following is to ensure the vehicle to reach and follow a desired Cartesian path, starting from a given initial configuration. For this task, it involves the separate construction of the geometric path and the dynamic assignment, namely emphasizing spatial convergence as a primary task, while considering the dynamic aspect to be of secondary importance. In this sense, path following represents a more flexible alternative compared to trajectory tracking (Breivik and Fossen, 2005a; Zheng et al., 2017a).

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There have been various efforts to develop intelligent controllers for path following control of an AUV in two-dimensional (2D) horizonal or vertical plane, such as feedback linearizing controller (Xiang et al., 2016b), backstepping controller (Lapierre and Soetanto, 2007; Xiang et al., 2015b), fuzzy controller (Guo et al., 2003), sliding mode controller (Chen et al., 2016), neural network controller (Peng et al., 2017a) and so on. These works consider unknown environmental disturbances, model uncertainty, and smooth transition of different configurations. Similar research methods can be found in path following and trajectory tracking control of MWRs, USVs and ROVs moving in the horizontal plane (Peng et al., 2013, 2017b; Chen and Tian, 2015; Wang et al., 2017c; Zheng et al., 2017b).

In fact, it is difficult to design an AUV path following controller from 2D decoupled control to three-dimensional (3D) coupled control (Cui et al., 2016; Zheng et al., 2017c; Xiang et al., 2017a). To the best of our knowledge, there have been few studies concerning 3D path following problem for an underactuated AUV exposed to environmental disturbances. A nonlinear 3D path following controller for an underactuated AUV was first proposed in (Encarnacao and Pascoal, 2000), while the singularity existed. This limitation was partially removed by introducing a virtual target point on the path in (Breivik and Fossen, 2005b), where another contribution was to first define line-of-sight (LOS) guidance angles in 3D space in order to achieve path following. Subsequently, many researchers followed and improved this LOS guidance law in kinematics and adopt multifarious intelligent controllers in dynamics to achieve path following control (Caharija et al., 2016; Miao et al., 2017b; Peymani and Fossen, 2015). More precisely, in Peymani and Fossen (2015), the virtually constrained motion control method was introduced and the fundamental principles of Lagrange mechanics were used to derive control laws. In Caharija et al. (2016), a cascaded framework composed of integral LOS guidance and a feedback linearizing proportional-derivative controller was developed for underactuated marine vehicles. Different from Breivik and Fossen (2005b), Aguiar built the tracking error in the body-fixed frame and adopted supervisory adaptive control and a nonlinear Lyapunov-based tracking control law to steer an underactuated AUV along a desired helix path (Aguiar et al, 2007). In addition, Do adopted Lyapunov's direct method, backstepping and parameter projection techniques to force an underactuated AUV to follow a predefined path despite of environmental disturbances and model uncertainty (Do et al., 2004). Yet, these controllers required substantial computational time and power due to the relatively complex derivations and decision making process.

As mentioned, some intelligent controllers require substantial computational time and power, which may not be applicable for the actual onboard controller of an AUV. In addition, a desired surge speed is often given in classic 3D path following for an underactuated AUV (Aguiar et al, 2007; Breivik and Fossen, 2005b; Caharija et al., 2016; Do et al., 2004; Peymani and Fossen, 2015), which results in the failure in determining the desired resultant speed due to drift effects in sway and heave. Motivated by those considerations, this paper releases the restriction on the given speed in 3D path following, and designs a simplified nonlinear single-input fuzzy controller with small calculation to achieve robust 3D path following. More specifically, the main contributions are enumerated as:

1. In order to solve the problem of the underactuated configuration in heave and sway, a novel 3D LOS guidance law is proposed to transform 3D path following position and orientation errors into controlled guidance speeds, which also reduces the dynamics following system form second-order to first-order. Different from Breivik and Fossen (2005a, 2005b), Miao et al. (2017b), the proposed LOS guidance law for 3D path following is based on the equivalent coordinate transformation among the resultant speed frame, body-fixed frame and inertial frame, which rigorously represents the relationship between the pitch, yaw, azimuth and elevation angles.
2. Compared to the double-input fuzzy controller (Guo et al., 2003; Xiang et al., 2017a), a single-input fuzzy path following controller is proposed in the dynamics layer. As an extension of planar motion (Ishaque et al., 2010, 2011), the single-input fuzzy controller is redesigned based on nonlinear technique to address the problem of 3D coupled motion with unknown environmental disturbances. In addition, the tracking errors of the AUV system under the nonlinear single-input fuzzy controller are proved to be uniformly ultimately bounded.
3. The sensitivity analysis is adopted to suggest that the nonlinear single-input fuzzy design with convergent membership function distribution and small slope for the single input have better robustness against environmental disturbances than the linear single-input fuzzy design, and then numerical simulation validates the result of the sensitivity analysis as well as the robust performance of this nonlinear single-input fuzzy controller in 3D path following of an underactuated AUV exposed to unknown environmental disturbances.

The rest of this paper is organized as follows: Problem statement of 3D path following for an underactuated AUV is presented in Section 2. In Section 3, the improved 3D guidance law in kinematics is designed for an underactuated AUV. Subsequently, a simplified nonlinear single-input fuzzy controller is proposed in dynamics. Numerical simulation results are given in Section 4 to illustrate the robust performance. Section 5 contains some remarks and discussions.

2. Problem statement

This section describes the modeling of an underactuated AUV moving in 3D space and formulates the problem of 3D path following control.

2.1. AUV modeling

For an AUV in 3D space, the general kinematics model can be described by six motion components in surge, sway, heave, roll, pitch, and yaw directions. Due to the existence of a metacentric height between centers of gravity and buoyancy which can generate an enough large restoring moment to passively stabilize the roll oscillation, neglecting the roll motion dynamics is a common assumption for slender-body AUVs, i.e., the roll angle $\phi = 0$ and the roll rate $p = 0$ (Miao et al., 2017b; Xiang et al., 2017a). According to Do and Pan (2009), the kinematics equations of a five-degrees-of-freedom AUV are

$$\begin{cases} \dot{x} = \cos(\theta)\cos(\psi)u - \sin(\psi)v + \sin(\theta)\cos(\psi)w \\ \dot{y} = \cos(\theta)\sin(\psi)u + \cos(\psi)v + \sin(\theta)\sin(\psi)w \\ \dot{z} = -\sin(\theta)u + \cos(\theta)w \\ \dot{\theta} = q \\ \dot{\psi} = r/\cos(\theta) \end{cases} \tag{1}$$

where x, y, z are coordinates of the origin of the body-fixed frame $\{B\}$ of the AUV expressed in the inertial frame $\{I\}$, and θ and ψ define its pitch angle and yaw angle, respectively. u, v, w, q and r denote its body-fixed linear and angular speeds.

According to Do and Pan (2009), the dynamics equations of a five-degrees-of-freedom AUV can be simplified as

$$\begin{cases} \dot{u} = \dfrac{m_{22}}{m_{11}}vr - \dfrac{m_{33}}{m_{11}}wq - \dfrac{d_{11}}{m_{11}}u + \dfrac{\tau_u}{m_{11}} + \dfrac{\tau_{Eu}}{m_{11}} \\ \dot{v} = -\dfrac{m_{11}}{m_{22}}ur - \dfrac{d_{22}}{m_{22}}v + \dfrac{\tau_{Ev}}{m_{22}} \\ \dot{w} = \dfrac{m_{11}}{m_{33}}uq - \dfrac{d_{33}}{m_{33}}w + \dfrac{\tau_{Ew}}{m_{33}} \\ \dot{q} = \dfrac{m_{33} - m_{11}}{m_{55}}uw - \dfrac{d_{55}}{m_{55}}q - \dfrac{Gh\sin(\theta)}{m_{55}} + \dfrac{\tau_q}{m_{55}} + \dfrac{\tau_{Eq}}{m_{55}} \\ \dot{r} = \dfrac{m_{11} - m_{22}}{m_{66}}uv - \dfrac{d_{66}}{m_{66}}r + \dfrac{\tau_r}{m_{66}} + \dfrac{\tau_{Er}}{m_{66}} \end{cases} \tag{2}$$

where $m_{(\cdot)}$ express system inertia coefficients, $d_{(\cdot)}$ denote hydrodynamic