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Diving control of Autonomous Underwater Vehicle based on improved active disturbance rejection control approach

Yuxuan Shen [a,*], Keyong Shao [a], Weijian Ren [a], Yurong Liu [b,c]

[a] School of Electrical and Information Engineering, Northeast Petroleum University, Daqing 163318, China
[b] Department of Mathematics, Yangzhou University, Yangzhou 225002, China
[c] Communication Systems and Networks (CSN) Research Group, Faculty of Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia

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ABSTRACT

The control problem of Autonomous Underwater Vehicle (AUV) is a very challenging one since the mathematical model of AUV is characterized by high nonlinearity, strongly coupling and time-varying features. In this paper, our aim is to design a diving active disturbance rejection controller for AUV. Firstly, a mathematical model of AUV is established, and the mathematical model is subsequently decoupled into three subsystems including speed control model, diving control model and steering control model. Then, an improved tracking differentiator is employed, which can provide better noise attenuation performance and avoid the chattering phenomenon as compared to the traditional tracking differentiator. After that, the controller is designed by using the active disturbance rejection control (ADRC) with the improved tracking differentiator. Finally, simulations are given to shown the effectiveness of the developed control scheme.

1. Introduction

With the rapid developments of the technology of vehicles, the Autonomous Underwater Vehicle (AUV) has been extensively studied by academic researchers and successfully applied in an extensive range of areas such as rescue, resource exploration, military, and oil detection, see for example [1,2]. Consequently, a variety of significant results concerning on the analysis and synthesis for AUV have been reported in the literature (see, e.g. [3–9] and the references therein). In some applications, the AUV is required to rise and dive fast, and have the ability to hover at the required depth. Hence, an effective controller is needed to meet the desired requirements. As such, the diving control problem of AUV has been an attractive research topic. Note that the system of AUV is characterized by high nonlinearity, strongly coupled and uncertainty of the complicated hydrodynamic. Unfortunately, the traditional control methods cannot meet the desired control requirements. Hence, it is of important significance to deal with those features so as to realize the certain control requirements for AUV.

During the past decades, many alternative control schemes have been reported in the literature including PID controller, H_∞ controller, fuzzy controller, adaptive controller, and sliding mode fuzzy controller, see [10–18] for some recent publications. Among them, a six-degrees-of-freedom adaptive controller has been designed in [10] for AUV with unknown dynamic parameters. Accordingly, the developed adaptive controller has been applied on omnidirectional intelligent navigator (ODIN) to verify the superiority of the proposed control method. In [13], a sliding mode fuzzy controller has been constructed for AUV and sufficient conditions have been given to ensure the stability and robustness of the addressed control system. Among the existing control methods, it is difficult to ensure the stability and robustness of the control system based on the fuzzy controller. For the adaptive control, the updated parameters are not always convergent, and the internal and external model principle needs the beforehand information of the unknown disturbance. It should be mentioned that the active disturbance rejection control (ADRC) approach in [19] does not depend on the accurate model of the plant. Moreover, the ADRC method has advantages of strong adaptability and robustness to the system uncertainties and external unknown disturbances, and it does not need the beforehand information of the unknown disturbance and also can ensure the stability.

Filtering is an important measure to inhibition and prevention the disturbance, it has been studied in many literature (see, e.g.

* Corresponding author. Tel.: +86 139 3688 4937.
E-mail addresses: shenyuxuan5973@163.com (Y. Shen), shaokeyong@tom.com (K. Shao), renwj@126.com (W. Ren).

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[20–26]). Tracking differentiator is an important component of ADRC and it can filter the input signal and produce its differential signal [27–30]. The tracking differentiator in the literature can be generally classified into two types: linear high order tracking differentiator [31–33] and nonlinear second-order tracking differentiator [34]. The linear tracking differentiator has the advantages of using less parameters and easy-to-design, but there exists the trade-off between the rapidity and stability. Hence, the nonlinear second-order tracking differentiator has been commonly adopted. It should be pointed out that it is very important to choose a proper tracking differentiator and then realize the desired control performance requirements when designing the tracking differentiator.

Motivated by the above discussions, we aim to investigate the diving control problem for AUV based on the ADRC method. Firstly, the mathematical model of AUV is established and decoupled. Subsequently, an improved tracking differentiator is introduced which combines the advantages of the linear and nonlinear tracking differentiator. The newly adopted tracking differentiator can provide better noise attenuation performance and avoid the chattering phenomenon compared to the traditional tracking differentiator. Furthermore, based on the ADRC approach, the controller is constructed to ensure the desired control requirements. Finally, a simulation example is offered to demonstrate the feasibility and usefulness of the proposed control approach. The main contributions of this paper lie in: 1) a new tracking differentiator is proposed to improve the disturbance attenuation ability of the ADRC; and 2) a new controller based on the ADRC approach is designed for AUV diving control.

The organization of the rest of this paper is as follows. In Section 2, the problem under consideration is given, and the mathematical model of AUV is established and decoupled. The improved tracking differentiator is presented and its stability is proved in Section 3. In Section 4, the diving active disturbance rejection controller is designed. The simulations are provided in Section 5, and we conclude the paper in Section 6.

2. Mathematical model of AUV and decoupling

2.1. Mathematical model of AUV

In order to establish the mathematical model of AUV, various factors should be taken into consideration such as damping and lift forces, Coriolis and centripetal forces, hydrodynamic drag, gravity and buoyancy, and thrust. Moreover, there are two reference frames should be considered to derive the mathematical model of AUV, i.e. the earth-fixed reference frame and the body-fixed reference frame, which are shown in Fig. 1.

As shown in Fig. 1, the origin of the earth-fixed reference frame (the left one) is determined by the surface of the ocean, and the origin of the body-fixed reference frame (the right one) is the center of gravity in the AUV. As in [35], the notations describing the motion of AUV are defined in Table 1.

The model of the nonlinear AUV motion can be divided into two parts: 1) kinematics part, which deals with the geometric aspects of motion; and 2) dynamics part, which describes the forces that contribute to the motion. In the sequel, let us state the kinematics and dynamics parts, respectively.

(1) Vehicle kinematics

By using some kinematic equations, we can convert the body-fixed velocity and rotation rate into the change in earth-fixed position and attitude. The linear and angular velocities are denoted by the vector $\boldsymbol{v} = [\boldsymbol{v}_1 \quad \boldsymbol{v}_2]^T = [u \quad v \quad w \quad p \quad q \quad r]^T$, the positions and angles are represented by the vector $\boldsymbol{\eta} = [\boldsymbol{\eta}_1 \quad \boldsymbol{\eta}_2]^T = [x \quad y \quad z \quad \phi \quad \theta \quad \psi]^T$. As

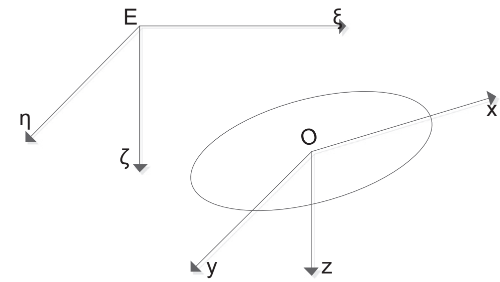

Fig. 1. The reference frames of the AUV.

Table 1
Notations of the AUV.

	x-direction	y-direction	z-direction
Linear velocities	u	v	w
Angular velocities	p	q	r
Forces	X	Y	Z
Moments	K	M	N
Positions	x	y	z
Euler angles	φ	θ	ψ

shown in [36], the six degrees of freedom (DOF) kinematic equation can be given by

$$\dot{\boldsymbol{\eta}} = \begin{bmatrix} \boldsymbol{J}_1 & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{J}_2 \end{bmatrix} \begin{bmatrix} \boldsymbol{v}_1 \\ \boldsymbol{v}_2 \end{bmatrix} \tag{1}$$

where $\boldsymbol{J}_1$ is the rotation matrix from the body-fixed reference frame to the earth-fixed reference frame, $\boldsymbol{J}_2$ is the transformation matrix from the body-fixed angular velocity vector to the Euler angles rate vector, and

$$\boldsymbol{v}_1 = [u \quad v \quad w]^T, \ \boldsymbol{v}_2 = [p \quad q \quad r]^T,$$

$$\boldsymbol{J}_1 = \begin{bmatrix} \cos\theta\cos\psi & \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \sin\theta\cos\phi\cos\psi - \sin\phi\sin\psi \\ \cos\theta\sin\psi & \sin\phi\sin\theta\ \mathrm{in}\psi + \cos\phi\cos\psi & \cos\phi\sin\theta\ \sin\psi - \sin\phi\cos\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix},$$

$$\boldsymbol{J}_2 = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi\sec\theta & \cos\phi\sec\theta \end{bmatrix}.$$

(2) Vehicle dynamics

As in [36], the six DOF dynamics equation is represented as follows:

$$\boldsymbol{M}\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{D}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{G}(\boldsymbol{\eta}) = \boldsymbol{\tau}. \tag{2}$$

the left-hand side of Eq. (2) contains the inertial terms, Coriolis and centripetal terms, damping terms and the gravity and buoyancy forces and moments, the right-hand side of the equation contains the external forces and moments.

In Eq. (2), $\boldsymbol{M}$ denotes the inertia matrix which is the sum of rigid body inertia matrix $\boldsymbol{M}_{RB}$ and mass matrix $\boldsymbol{M}_A$, i.e.

,

$$\boldsymbol{M} = \boldsymbol{M}_{RB} + \boldsymbol{M}_A = \begin{bmatrix} m\boldsymbol{I}_{3\times3} & -m\boldsymbol{S}(\boldsymbol{r}_g^b) \\ m\boldsymbol{S}(\boldsymbol{r}_g^b) & \boldsymbol{I}_0 \end{bmatrix} + \begin{bmatrix} \boldsymbol{A}_{11} & \boldsymbol{A}_{12} \\ \boldsymbol{A}_{21} & \boldsymbol{A}_{22} \end{bmatrix},$$

where m is the mass of the AUV, $\boldsymbol{I}_{3\times3}$ is the identity matrix,