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Heading multi-mode control based on soft-switching for autonomous underwater vehicle☆

JunHe Wan, Bo He*, Yue Shen, WenQian Liu, Xin Ding, Shuang Gao

School of Information Science and Engineering, Ocean University of China, 238 Songling Road, Qingdao, China

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ABSTRACT

This paper aims to solve the problem that a single control method can't fit to each operating condition of heading control for autonomous underwater vehicle (AUV). A multi-mode strategy based on soft-switching is proposed, which can get better performance by smooth switching of control modes. The control mode consists of two levels, which is named as *two-level-mode* method. On the first level, the control mode is divided into six according to the operating state of AUV. On the second level, based on the existing mode the control mode is divided into three depending on AUV′ speed. In addition, the BB-PID controller is designed for heading control, as well as the sigmoid function is constructed to smoothly switching at different speed without saltation. The simulation and experiment results demonstrate that BB-PID controller achieves outstanding performance and the switching strategy is much more effective by comparing the RMS, RMSE, SSE between switching based on sigmoid function and switching based on threshold.

1. Introduction

The control of AUV is mainly divided into two types: horizontal heading control and vertical depth control. Especially the heading which controls the trajectory of AUV is a key technique. Much more research in recent decades has focused on this issue. The control strategies chiefly include: PID controller (Jalving, 1994; Khodayari and Balochian, 2015; Chen et al., 2009), sliding mode controller (Wang et al., 2012; Rosendo et al., 2016; Cui et al., 2016), $H\infty$ controller (Silvestre and Pascoal, 2007; Mahapatra and Subudhi, 2017) and adaptive controller (Hassanein et al., 2016)etc. However, heading control of AUV is so difficult due to coupled nonlinearities, parameter uncertainties resulting from poor knowledge of hydrodynamic coefficients, and external disturbances such as ocean currents and waves. The motion characteristics of AUV are quite different under a great variety of disparate operating conditions. Hence, there is no method can get excellent control efficiency under all of the operating condition, and unfortunately, some methods may perform better in this condition but much worse in another condition. Consequently, it is necessary to study the control strategy for AUV.

The multi-mode control is a changing control strategy with the running state of the system. In accordance with the actual operation of the system, the most appropriate real-time control algorithm can be selected with the intelligent multi-mode control. It can usually achieve a variety of comprehensive advantages of control strategy, so that the control performance of complex systems can get the best performance. This method has been explored and applied in military engineering, automobile, electric power and other industries, and that works well. The multi-mode control based on neural network for laser guidance missile provides good control over the nonlinear time-varying system with wide variation of parameters (Shen et al., 2000). A multi-mode control strategy based on fuzzy selector can get perfect control effect for the four-wheel-steering vehicle (Yang et al., 2010). Meanwhile, it demonstrates that the multi-mode control has better control effect than single one. The converter of a direct-drive permanent magnetic wind generation system in a micro-grid adopts an adaptive multi-mode power control algorithm (He et al., 2013). The maximum power point tracking algorithm is faster, more robust, and adaptive to changes of the environment than the conventional variable-step hill climbing search algorithm. For primary-side regulation (PSR) system, four-mode control strategy improves the efficiency under variety load conditions. The average efficiency can be improved about 3.6% compared with conventional system and the standby power is less than 10 mW under different conditions (Liu et al., 2017). A real-

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* Corresponding author.
E-mail address: bhe@ouc.edu.cn (B. He).

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time multi-mode energy management strategy for a plug-in fuel cell/battery electric vehicle, taking three typical processes (starting up, normal working, shutting down) into consideration. The strategy reduces fuel consumption and prolongs working lifetime of the fuel cell/battery system (Xu et al., 2014).

Accordingly, it is feasible to apply the multi-mode control in AUV. However in the literature reviewed, the multi-mode control strategy hasn't previously been reported for heading control of AUV. The major contributions of this work are highlighted as follows:

a. This two-level-mode method is proposed to divide the control mode. On the first level, the control mode is divided into six according to the operating state of AUV. On the second level, based on the existing mode the control mode is divided into three depending on AUV′ speed.
b. The BB-PID controller is designed by utilizing the complementary advantages of Bang-Bang, PID and Output-hold methods according to the characteristics of each mode. In this paper, the heading controller at middle speed is taken as an example, which is much the same as the high and low speed.
c. The soft-switching strategy based on sigmoid function is proposed for heading control at different speed. The steady-state output of the two controllers is employed as the upper and lower bounds of the sigmoid function. Within a small range before and after the switching time, the transition process of the controller is changed in accordance with the sigmoid function. With the help of the saturated, monotonic and smooth features of the sigmoid function, the switching is also stable and smooth.

The remainder of this paper is organized as follows: after a dynamic model of AUV in the next section, the division of control mode and the controller design are explained in Section 3. Section 4 describes the switching of control mode based on sigmoid function. In Section 5, a set of experimental comparisons are carried out in terms of accuracy and speed by simulations and experiments, while the results are also being discussed. Finally, Section 6 summarizes the key conclusions of this work.

2. Vehicle model

2.1. Establishing coordinate system

The notation, term and coordinate system are defined by SNAME (Society of Naval Architects and Marine Engineers, 1950). The world-fixed coordinate system (E-$\xi\eta\zeta$) has its origin E fixed to the earth. The body-fixed coordinate system (O-xyz) with origin O is moving reference frame that is fixed to AUV (see Fig. 1).

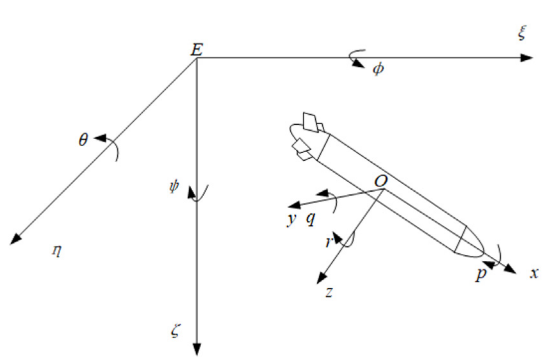

Fig. 1. Coordinate system of AUV.

Table 1
Notions used for AUV.

Vector	X-axis	Y-axis	Z-axis
Velocity	u	v	w
Angular velocity	p	q	r
Euler Angle	ψ	θ	φ
Force	X	Y	Z
Torque	K	M	N

For AUV, the six different motion components are conveniently defined as surge (u), sway (v), heave (w), roll (p), pitch (q) and roll (r). $\mathbf{v} = [\mathrm{u,\ v,\ w,\ p,\ q,\ r}]^T$ is the linear angular velocity with respect to the body-fixed reference frame, and $\tau = [\mathrm{X,\ Y,\ Z,\ K,\ M,\ N}]^T$ is the total forces and moments acting on AUV. The Euler angles are heading angle ψ, pitch angle θ and roll angle φ. The notations are summarized in Table 1.

2.2. Dynamic model of AUV

In general, the force on AUV can be divided into two categories: the one is the hydrodynamic force F_{vis} (or the resistance force) due to a vehicle moving in fluid, the other is the external force F_{else}, such as the rudder force, propulsion force, gravity and buoyancy, etc. The equation can be expressed as Equation (1) (Prestero, 2001; Liu et al., 2015; Fossen, 2011)

$$E\dot{\mathbf{v}} = F_{vis} + F_{else} \tag{1}$$

Where E is defined as Equation (2), considering xz plane of symmetry (pot/starboard symmetry)

$$E = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 & 0 & mz_G & 0 \\ 0 & m - Y_{\dot{v}} & 0 & -mz_G - Y_{\dot{p}} & 0 & -Y_{\dot{r}} \\ 0 & 0 & m - Z_{\dot{w}} & 0 & -Z_{\dot{q}} & 0 \\ 0 & -mz_G - Y_{\dot{p}} & 0 & I_x - K_{\dot{p}} & 0 & -K_{\dot{r}} \\ mz_G & 0 & -Z_{\dot{q}} & 0 & I_y - M_{\dot{q}} & 0 \\ 0 & -Y_{\dot{r}} & 0 & -K_{\dot{r}} & 0 & I_z - N_{\dot{r}} \end{bmatrix} \tag{2}$$

Where

m: AUV mass;
z_G: barycentric coordinate of AUV;
I_x, I_y, I_z: moments of inertia about x,y and z axes;
$X_{\dot{u}}$, $Y_{\dot{v}}$, $Y_{\dot{r}}$, $Z_{\dot{w}}$, $Z_{\dot{q}}$, $K_{\dot{p}}$, $K_{\dot{r}}$, $M_{\dot{q}}$, $N_{\dot{v}}$, $N_{\dot{r}}$: hydrodynamic coefficients.
$\mathbf{v} = [u, v, w, p, q, r]^T$: velocity (angular velocity) of six degrees of freedom.
$\dot{\mathbf{v}} = [\dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}]^T$: acceleration (angular acceleration) of six degrees of freedom.
$F_{vis} = [X_{vis}, Y_{vis}, Z_{vis}, K_{vis}, M_{vis}, N_{vis}]^T$: hydrodynamic forces and moments.