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Sliding mode tracking control of autonomous underwater vehicles with the effect of quantization

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ABSTRACT

This paper develops a trajectory tracking control law for autonomous underwater vehicles (AUVs) with the effect of states and control input quantization. A sliding mode control (SMC) scheme is proposed to conquer the quantization effect by introducing the bound of quantization error into the switching term of the SMC. A finite-time disturbance observer is proposed to observe the unknown time-varying disturbances. The stability analysis demonstrates that the designed tracking controller can force the AUV to track the reference trajectory and guarantee the asymptotic stability of the closed system. Simulation results illustrate the effectiveness of the proposed control method.

1. Introduction

In recent years, we have seen that autonomous underwater vehicles (AUVs) play an important role in many undersea applications especially in the ocean surveying and the oil and gas industry. Control of AUVs has received considerable attention with the rapid development of ocean engineering (Fossen, 2002; Li and Wang, 2013; Xiang et al., 2017a, b). Trajectory tracking control of AUVs is an important control problem in marine engineering and control community. However, AUVs suffer from complex subsea conditions such as model non-linearities, unknown hydrodynamic coefficients and disturbances (Xiang et al., 2017c). Therefore, from a practical point of view, the design of efficient controllers for AUVs is an important issue in the marine industry.

One of the control method for an AUV is the sliding mode control (SMC) method. As a robust control method, the SMC has attractive features in dealing with system uncertainties and disturbances (Yu et al., 2005; Zhu et al., 2011; Yang et al., 2013; Yu and Kaynak, 2017; Xiang et al., 2017d). A second-order SMC method is used to stabilize an AUV which has modeling errors and unknown environmental disturbances as shown in Joe et al. (2014). Benetazzo et al. (2015) use the SMC law to guarantee a fault-tolerant robust control for the dynamic positioning of an over-actuated offshore supply vessel. In Ma and Zeng (2015), a sliding mode controller is used to the distributed formation control of AUVs networked by sampled-data information. In Cui et al. (2016), the attitude of AUVs with input nonlinearities is controlled by using the SMC method. A dynamic region-based SMC scheme is designed for an AUV to reduce the energy demand in Ismail et al. (2016). In Sun et al. (2017), an adaptive integral SMC law is designed to track the desired path of a virtual ship.

All aforementioned control design for vessels did not take into account quantization. Quantization can be found in various control environments such as a network control environment. The quantization should be considered when digital networks are part of the feedback loop. Compared to the systems without quantization, the presence of quantization makes it more difficult to achieve the stability of the system due to the quantization effect on the control systems. For more information on quantization control, one can refer to Liberzon (2003); Fu and Xie (2015); Gao and Chen (2008) and the references therein. The SMC is an effective control method for dealing with the quantization due to the robust property of the control method. There have been some existing works on connecting the quantization control and SMC. Corradini and Orlando (2008) investigates stabilization problem for linear uncertain control systems with saturating quantized measurements by using a time-varying sliding surface. The quantization effect on the SMC systems is analyzed in Yan et al. (2016). In Liu et al. (2017), a SMC law is developed to arkovian jump systems with the quantization effect. Zheng et al. (2017) investigates quantized SMC problem in the unified delta operator system framework.

Quantization is a potential problem for control of AUVs since the state variables are required to be quantized and transmitted to the controller side in practical engineering. For example, in the off-shore oilfields systems the underwater robotics interact with the sensor nodes and control

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nodes via acoustic communications (Heidemann et al., 2006). Moreover, the communication problem should be considered in cooperative control of multiple AUVs as shown in Millán et al. (2014). In this paper, a new type of quantized SMC approach is developed for AUVs with quantized state and control input. The dynamical uniform quantization scheme is used to the design work. To the best for the authors' knowledge, it is the first time in the literature that the quantization effect is considered in the AUV control design. A disturbance observer is constructed to estimate unknown disturbances and the bound of quantization error is taken into the switching term of the SMC to handle the quantization effect.

The rest of the paper is organized as follows. Problem statement is presented in the next section, including the nonlinear model of the AUV, the structure of the control system with quantized state feedback and control input and the control objective. In Section 3, first, a finite time observer and the equivalent SMC method are used to control the AUV system without quantization. Second, a SMC method is developed to control the AUV system with quantized state feedback and the dynamical uniform quantizer policy is proposed to adjust the quantization parameter. Finally the result is extended to control the AUV system with both quantized state feedback and control input. Numerical simulation results are given in Section 4 to illustrate the performance of the proposed controller. Section 5 contains some concluding remarks.

2. Problem formulation

2.1. Kinematic and dynamic model of the AUV

The general dynamic mode of the AUV in the horizontal plane can be described by the motion components in the surge, sway and yaw directions with the neglecting of the motions in heave, roll and pitch. The kinematic and dynamic model of the AUV can be described as follows:

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}(\psi)\boldsymbol{\upsilon} \tag{1}$$

$$\boldsymbol{M}\dot{\boldsymbol{\upsilon}} = -\boldsymbol{C}(\boldsymbol{\upsilon})\boldsymbol{\upsilon} - \boldsymbol{D}(\boldsymbol{\upsilon})\boldsymbol{\upsilon} + \boldsymbol{\tau} + \boldsymbol{d}(t) \tag{2}$$

where $\boldsymbol{\eta} = [x, y, \psi]^T$ is the position vector in the earth-fixed frame, x is the surge position, y is the sway position, $\psi \in [0, 2\pi]$ is the heading of the ship, $\boldsymbol{\upsilon} = [u, v, r]^T$ is the velocity vector in the body-fixed frame, u is the surge velocity, v is the sway velocity and r the yaw rate of the ship. $\boldsymbol{\tau} = [\tau_1, \tau_2, \tau_3]^T$ is the control input, consisting of control forces τ_1 in surge and τ_2 in sway, and moment τ_3 in yaw. $\boldsymbol{d}(t) = [d_1(t), d_2(t), d_3(t)]^T$ is the disturbance vector, where $d_1(t)$ and $d_2(t)$ are the disturbance forces in surge and sway, and $d_3(t)$ is the disturbance moment in yaw.

The rotation matrix is given by

$$\boldsymbol{R}(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{3}$$

Note that $||\boldsymbol{R}|| = 1$ and $||\cdot||$ presents the two-norm of a vector or a matrix. $\boldsymbol{C}(\boldsymbol{\upsilon})$ is the Coriolis and centripetal forces. $\boldsymbol{D}(\boldsymbol{\upsilon})$ is the restoring force vector. $\boldsymbol{M}$ is the inertia matrix. In detail,

$$\boldsymbol{C}(\boldsymbol{\upsilon}) = \begin{bmatrix} 0 & 0 & -m_v v \\ 0 & 0 & m_u u \\ m_v v & -m_u u & 0 \end{bmatrix}$$

$\boldsymbol{D}(\boldsymbol{\upsilon}) = \mathrm{diag}\{d_u, d_v, d_r\}$, $\boldsymbol{M} = \mathrm{diag}\{m_u, m_v, m_r\}$, $m_u = m - X_{\dot{u}}$, $m_v = m - Y_{\dot{v}}$, $m_r = I_z - N_{\dot{r}}$, $d_u = -X_u - X_{|u|u}|u|$, $d_v = -Y_v - Y_{|v|v}|v|$, $d_r = -N_r - N_{|r|r}|r|$, where m is the AUV mass, $X_{(\cdot)}$, $Y_{(\cdot)}$, $N_{(\cdot)}$ are hydrodynamic derivatives of the system, and $d_{(\cdot)}$ is hydrodynamic damping effect.

Assumption 1. The disturbances in the AUV system *(2) are unknown bounded terms.* $d_i(t)$ *is differentiable and* $\dot{d}_i(t)$ *has a known Lipshitz constant* $L_i > 0$, $i = 1, 2, 3$.

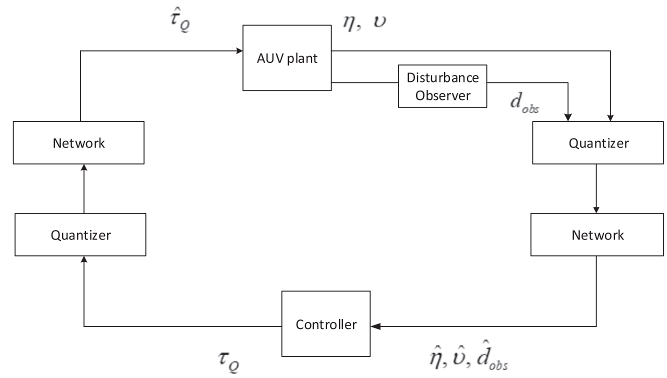

Fig. 1. The structure of the AUV control system.

2.2. The structure of the AUV control system with quantization

The structure of the AUV control system is shown in Fig. 1. The AUV plant and the controller are connected via networks. In the network communication channel, the state vectors $\boldsymbol{\eta}$, $\boldsymbol{\upsilon}$ and the observer output $\boldsymbol{d}_{obs}$ should be quantized then transmitted to the controller, respectively. Similarly, the output of controller $\boldsymbol{\tau}_Q$ should be quantized before transmitting to the plant. For convenience, we use the signal $\hat{}$ to present the quantized value of variables in the following part. The control input with quantized state feedback is denoted by signal $\boldsymbol{\tau}_Q$. Moreover, the variable matrices $\boldsymbol{R}(\boldsymbol{\upsilon})$, $\boldsymbol{C}(\boldsymbol{\upsilon})$ and $\boldsymbol{D}(\boldsymbol{\upsilon})$ in (1)–(2) with quantized state feedback are denoted as $\boldsymbol{R}_Q$, $\boldsymbol{C}_Q$ and $\boldsymbol{D}_Q$ respectively.

A quantizer can be considered as a device that converts a real-valued signal into piecewise constant one. Denoting that μ is the quantization parameter, here the uniform quantizer is defined as

$$\hat{\boldsymbol{z}} = \mu \cdot \mathrm{round}(\boldsymbol{z}/\mu) \tag{4}$$

where $\boldsymbol{z} \in R^n$ is the vector to be quantized, $\hat{\boldsymbol{z}} \in R^n$ is the quantized measurement and the function round () denotes the nearest integer operation which defines that positive elements with a fractional part of 0.5 round up to the nearest positive integer whereas negative elements with a fractional part of -0.5 round down to the nearest negative integer. Denoting the quantization error as $\boldsymbol{e_z}(t) = \hat{\boldsymbol{z}} - \boldsymbol{z}$, then we obtain $||\boldsymbol{e}_z(t)|| \le \sqrt{n}\mu/2$, where n is the dimension of $\boldsymbol{z}$.

2.3. Control objective

In this paper, we aim at trajectory tracking control of an AUV in the presence of unknown disturbance and quantization effect. The variables of both the plant state and the output of controller are quantized. The objective is to design a SMC scheme such that the states of closed system can be stabilized with the effect of quantization.

Assume that quantizers in the side of the AUV plant to controller are dynamical uniform quantizers with discrete adjustment of the quantization parameter. The reason to design a dynamic quantizer with discrete adjustment of the quantization parameter is that it can drive the system trajectories onto the sliding surface, instead of just to some neighbor of the sliding surface (Zheng and Yang, 2014). Static uniform quantizers are used in the side of controller to plane. The static quantizers are common because of its simplicity in construction.

3. Sliding mode control with quantization

To show the quantization effect on AUVs clearly, in this section, first the equivalent SMC method is used to control the system without quantization. Then quantization is brought to the system and the