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Adaptive neural network-based backstepping fault tolerant control for underwater vehicles with thruster fault

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ABSTRACT

A thruster fault tolerant control (FTC) method is developed for underwater vehicles in the presence of modelling uncertainty, external disturbance and unknown thruster fault. The developed method incorporates the sliding mode algorithm and backstepping scheme to improve its robustness to modelling uncertainty and external disturbance. In order to be independent of the fault detection and diagnosis (FDD) unit, thruster fault is treated as a part of the general uncertainty along with the modelling uncertainty and external disturbance, and radial basis function neural network (RBFNN) is adopted to approximate the general uncertainty. According to the Lyapunov theory, control law and adaptive law of RBFNN are derived to ensure the tracking errors asymptotically converge to zero. Trajectory tracking simulations of underwater vehicle subject to modelling uncertainty, ocean currents, tether force and thruster faults are carried out to demonstrate the effectiveness and feasibility of the proposed method.

1. Introduction

Underwater vehicles are widely used to accomplish the assigned missions in the complex marine environment (Carreno et al., 2010). Trajectory tracking is an important part in the process of missions, which requires high reliability and robustness. Faults, especially thruster faults, would affect the stability, even the safety of the whole underwater vehicle system, making the trajectory tracking more complicated for underwater vehicle subject to modelling uncertainty and ocean current disturbance. Therefore it is important to develop FTC algorithm to ensure the security and reliability of the underwater vehicle system (Omerdic and Roberts, 2004; Podder and Sarkar, 2001).

Generally, FTC method can be classified into two types: passive FTC and an active FTC (Zhang and Jiang, 2008). As for underwater vehicles, most references focused on active FTC in the recent decades. Podder and Sarkar (2001) proposed an active FTC approach with FDD unit to allocate the thrust based on weighted pseudo-inverse scheme to track a given task-space motion trajectory. Omerdic and Roberts (2004) integrated self-organizing maps and fuzzy logic clustering to achieve fault diagnosis; and then the FTC method made use of the thruster information to adopt the weighted pseudo-inverse scheme to compensate fault effect. Soylu et al. (2008) proposed a chattering-free sliding mode FTC, where an adaptive term replaced the conventional discontinuous switching term and then a thruster allocation scheme based on L infinity-norm was proposed to allocate thruster force. Zhu et al. (2011) proposed a thruster reconfiguration control approach based on quantum-behaved particle swarm optimization, however, the real-time problem of online quantum-behave particle swarm optimization reconfiguration approach was not resolved. Huang et al. (2014) established an energy function according to the duality principle and integrated the assumed thruster fault information to develop FTC algorithm and used a recurrent neural network to compensate the thruster fault effect. Corradini and Orlando (2014) proposed a robust observer-based fault tolerant control scheme for underwater vehicles. The references about FTC of underwater vehicles cited in the mentioned-above are active FTC methods. It is worth noting that there exists an important assumption in the all above references, that is, the FDD unit should accurately and timely provide fault information to FTC. However, underwater vehicles suffer from external disturbance, which leads the above assumption to be too strict to misjudge or miss faults by a FDD unit. Dearden and Ernits (2013) claimed that it is difficult to distinguish the case where thruster is impaired or entangled from the case where the vehicle is moving against a strong current. Therefore, the paper investigates a passive FTC method to make underwater vehicles could maintain good control performance, no matter whether a thruster fault has occurred.

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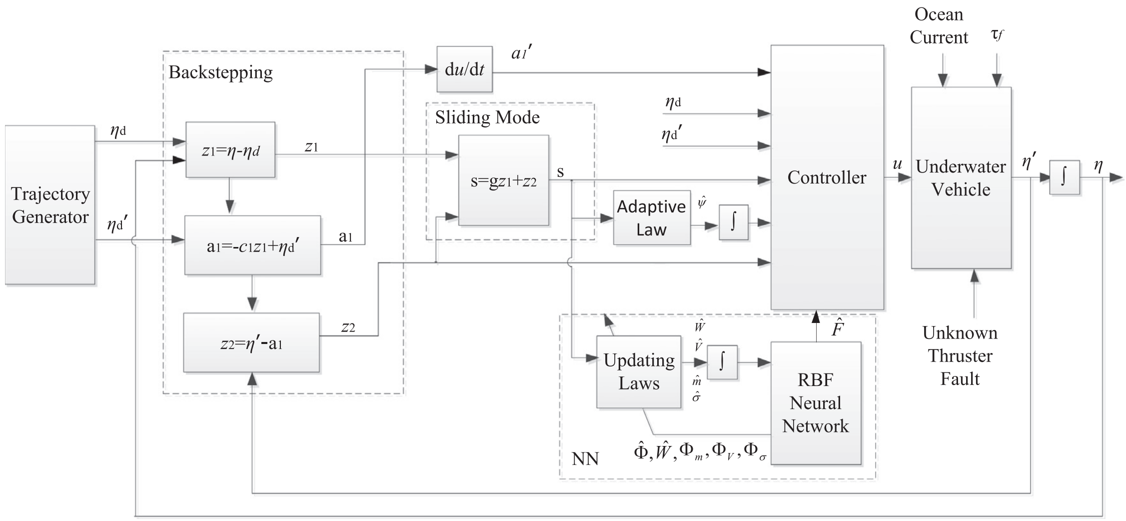

Fig. 1. Control system scheme.

Backstepping control has been widely used for underwater vehicles, due to its simple design procedure to stabilize system states by step-by-step recursive process. A backstepping-based low and high gain approach was designed for marine vehicles (Bateman et al., 2009). Morishita and Souza (2014) proposed modified observer backstepping controller for a dynamic positioning system. Bing et al. (2014) developed a bioinspired filtered backstepping tracking control for submarine vehicle. In other nonlinear systems, backstepping technique is widely applied to design FTC methods. Shaocheng et al. (2014) proposed adaptive fuzzy decentralized FTC scheme combining backstepping technique for large-scale systems. Bin et al. (2014) developed adaptive neural observer-based backstepping FTC method for near space vehicle, where the design of FTC was dependent of observer design. Khebbache et al. (2015) investigated active FTC problem for nonlinear systems subject to sensor fault in the frame of backstepping technique. In order to improve the robustness to external disturbance and modelling uncertainty, some researchers have integrated sliding mode algorithm with backstepping technique (Bartolini et al., 1996, 2000). Qikun et al. (2014) proposed adaptive fuzzy observer-based active FTC method in the integration sliding mode and backstepping technique, where the threshold was an important parameter to achieve FDD. Tong et al. (2014) presented dynamic surface control design approach based on backstepping technique, where fuzzy state observer is designed to the unmeasured states and an adaptive term was designed to compensate actuator faults. To the authors' knowledge, there are no references to investigate backstepping-based FTC method for underwater vehicles by treating the unknown thruster fault as a part of the general uncertainty, including modelling uncertainty and external disturbance.

Motivated by the above considerations, the paper investigates a passive FTC algorithm for underwater vehicles considering the modelling uncertainties, external disturbances and thruster faults without the FDD unit. In the framework of backstepping and sliding mode technique, adaptive FTC method is developed based on RBFNN for underwater vehicles, where the unknown thruster fault is treated as a part of the general uncertainty and RBFNN is used to approximate the general uncertainty. In comparison with the existing works, the main contribution of the paper can be summarized in the following: (1) unlike in Soylu et al. (2008), where the ocean current is simulated as constant, the varying ocean current model (Fossen, 2011) is described and used in the simulations, to be more practical. (2) Different from the references (Sarkar et al., 2002; Soylu et al., 2008; Zhu and Kong, 2007), where the thruster fault is assumed to be known exactly and timely, and also unlike in references (Qikun et al., 2014; Tong et al., 2014), where observer was designed to estimate the fault, or observer together with adaptive term was used to compensate the faults, the paper treats the thruster fault as a part of the general uncertainty, including with modelling uncertainty and external disturbance. And RBFNN is designed to be approximate the general uncertainty on-line without the need of the FDD unit. (3) By using Lyapunov theory and Barbalat's lemma, the asymptotical stability of the tracking errors are proved taking into modelling uncertainty, ocean current disturbance and thruster fault.

The remainder of this paper is organized as follows. In Section 2, underwater vehicle model in ocean environment is described. In Section 3, it proposed an adaptive sliding mode fault tolerant control based on backstepping algorithm, where RBFNN is adopted to estimate the modelling uncertainty, ocean current disturbance and unknown thruster fault, and the stability is analysed based on Lyapunov theory and Barbalat's lemma. Simulations of Canadian Scientific Submersible Facility ROPOS underwater vehicle are performed in Section 4. Conclusions are given in Section 5.

2. Dynamics model and problem statement

2.1. Dynamics model of underwater vehicle

The dynamic motion equations of underwater vehicles in the earth-fixed frame can be represented as (Fossen, 2011)

$$\dot{\eta} = \dot{\eta}$$
$$M_\eta \ddot{\eta} + C_{RB\eta}\dot{\eta} + C_{A\eta}\dot{\eta}_r + D_\eta \dot{\eta}_r + g_\eta + \tau_f = \tau \quad (1)$$

where, $M_\eta = MJ^{-1}$; $C_{RB\eta} = \left[C_{RB}(v) - MJ^{-1}\dot{J}\right]J^{-1}$; $C_{A\eta} = C_A(v_r)J^{-1}$; $D_\eta = D(v_r)J^{-1}$; $g_\eta = g(\eta)$; $\dot{\eta}_r = J(\eta)v_r$; $\eta = [x\ y\ z\ \varphi\ \theta\ \psi]^T$ denotes the position and orientation vector in the earth-fixed frame and $v = [u\ v\ w\ p\ q\ r]^T$ denotes velocity vector in the body-fixed frame, J is the transformation matrix between the earth-fixed frame and the body-fixed frame; M is the inertial matrix including the added mass; C_{RB} is rigid-body Coriolis and Centripetal matrix; C_A is added Coriolis and Centripetal matrix; D is the drag coefficient matrix; $g(\eta)$ is the vector of combined gravitational and buoyancy forces and moments; τ_f is the external force caused by tether; τ is the control forces and moments acting on the underwater vehicle centre of mass; v_r is the vehicle velocity relative to ocean current and $v_r = v - v_c$, v_c is the ocean current velocity in the body-fixed frame.

Thruster is the most common and important resource of faults (Omerdic and Roberts, 2004). And the effect of thruster fault can