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Adaptive fault tolerant control and thruster fault reconstruction for autonomous underwater vehicle

Xing Liu [a,b,*], Mingjun Zhang [a], Feng Yao [a]

[a] College of Mechanical and Electrical Engineering, Harbin Engineering University, Harbin, 150001, China

[b] Department of Electronics and Computer Science, University of Southampton, Southampton, SO17 1BJ, UK

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ABSTRACT

This paper investigates adaptive fault tolerant control and fault reconstruction problem for AUV subject to ocean current disturbance and modelling uncertainty. At first, a virtual closed-loop system based adaptive fault tolerant control method is developed. In this method, the constructed virtual closed-loop system is mainly used to deal with the influence of the initial tracking error in an ideal environment and avoid the serious chattering phenomenon in control output. Then with respect to fault reconstruction in the framework of fault tolerant control, an improved second-order sliding mode observer is constructed to estimate the thruster fault effect. The feedback of the developed observer consists of different functions of the estimation errors, including fractional function, signature function and integral function etc. Furthermore, the stability analysis is given based on Lyapunov theory. Finally, a series of simulations are performed on an over-actuated AUV for different desired trajectories and different types of thruster faults under the condition of the simulated ocean current environment. The comparative simulation results demonstrate the effectiveness and feasibility of the new design.

1. Introduction

Due to their advantages in terms of reliability and flexibility, autonomous underwater vehicles (AUVs) have been widely used for observation of underwater structure and other scientific and commercial missions (Choi et al., 2013; Shen et al., 2017; Yu et al., 2017). For example, AUVs have been used as platforms with survey sensors close to the inspected objects (such as reservoir dams) to acquire high-quality results without other disturbances (Sun et al., 2012). AUVs operate in the unknown and complicated ocean environment without any umbilical cable. Safety and reliability are two most important features for AUVs (Dearden and Ernits, 2013; Hamilton et al., 2007). Thrusters are the most important propulsion system, but also are liable to faults, such as entangled fault or impaired fault (Omerdic and Roberts, 2004). Once thruster fault is occurred, control performance may be degraded, or even the loss of AUVs probably occurs, if continuing to operate as before without any alarms (Zhang et al., 2015b).

Many thruster fault diagnosis methods have been developed for AUVs, classifying into model based diagnosis, data-driven based quantitative diagnosis and qualitative diagnosis (Zhang et al., 2015a). The latter two methods are relatively complicated, and in general would take up too many computer resources. The model based diagnosis methods are mainly achieved based on observers (Chu and Zhang, 2014). In model based fault diagnosis, one commonest way (Corradini et al., 2011) is to calculate the residual error between the estimated AUV states provided by observers and the real AUV states provided by sensors, and then to detect, isolate and identify thruster fault based on the residual error. However, in this kind of diagnosis method, threshold values are required, but also difficult to be determined in priori. Another typical way is to directly estimate the thruster fault effect by fault reconstruction (Chu and Zhang, 2014). In this study, fault reconstruction shall be investigated.

In fault reconstruction research, the main procedures can be summarized: a sliding mode observer with finite-time convergence is built at first to estimate the system states and then the concept "equivalent output injection" is used to obtain the estimated value of fault effect (Rahme and Meskin, 2015). (Yan and Edwards, 2007) and (Alwi et al., 2012) investigated fault reconstruction problem in a fixed feedback controller for a nonlinear system with bounded uncertainty or a linear parameter varying system, where the sliding mode observer was constructed based on the proportion term and signature term of the estimated output error. Also fault reconstruction was investigated based on the combination of high gain observer and sliding mode observer for nonlinear system (Veluvolu et al., 2014), where the control input was fixed and the fault effect is independent with control input. In order to

* Corresponding author. College of Mechanical and Electrical Engineering, Harbin Engineering University, Harbin 150001, China.
E-mail addresses: E-mail address: liuxing20080724@gmail.com (X. Liu). liuxing0724@hrbeu.edu.cn (X. Liu).

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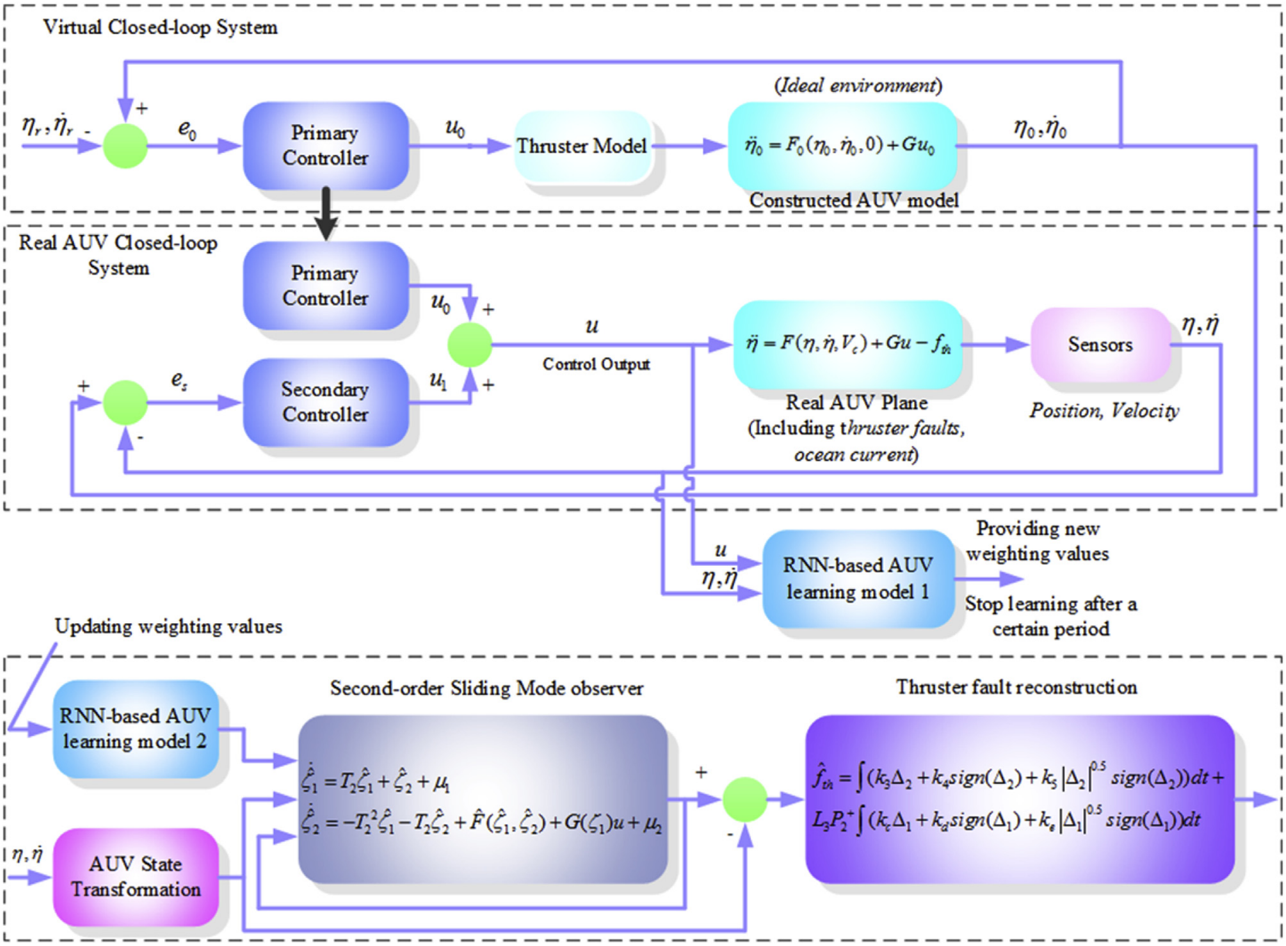

Fig. 1. Diagram of the developed adaptive fault tolerant control method and fault reconstruction.

improve the fault reconstruction precision, other observers with faster convergence speed have been applied to estimate the system states. Chu and Zhang (2014) developed a thruster fault reconstruction method on the basis of the terminal sliding mode observe structure in (Tan et al., 2010), and RBF neural network was used to estimate the unknown function in AUV model in the whole process of fault reconstruction. Besides, second-order sliding mode observer (Moreno and Osorio, 2008) was presented based on super twisting algorithm. Due to its advantage of finite-time convergence and the robustness to the bounded disturbances, second-order sliding mode observers have been applied in fault reconstruction, e.g., a novel fault reconstruction method was given based on second-order sliding mode observer with adaptive gains for PEM Fuel Cell Air-Feed system, where the fault was independent with control input.

In this paper, fault reconstruction is investigated based on second-order sliding mode observer for AUVs with thruster faults. In AUV field, the thruster fault effect is related with the controller output in general, rather than a simple function only related with time. Moreover, in order to guarantee AUV's reliability and safety even in the case of thruster faults, adaptive fault tolerant controller with good robustness to unknown thruster faults is used, where the thruster fault is considered as a part of the general uncertainty. The action of adaptive fault tolerant controller would reduce or even hide the fault thruster effect on the tracking performance. It will increase the difficulty of fault reconstruction, compared with in the case of the fixed controller.

Based on the above-mentioned consideration, thruster fault reconstruction is investigated in adaptive fault tolerant control system for AUVs. The paper develops an adaptive fault tolerant control method based on virtual closed-loop system and an improved second-order sliding mode observer based thruster fault reconstruction method. In the new design, at first, the adaptive fault tolerant controller is developed by using a virtual closed-loop system to separately compensate the effect of the initial tracking error and thruster fault, and the difference between the controlled planes in real system and the virtual system is counteracted based on the combination of neural network and PID type compensator. And then the thruster fault reconstruction is completed based on the second-order sliding mode observer, inspired by the observer structure in (Kommuri et al., 2016). In this paper, it is assumed that both AUV's position and velocity are measurable. And in the developed thruster fault reconstruction method, we design the feedback law in the observer structure based on the inertial term, fractional power function and signature term of the AUV's position and velocity estimation errors. Finally, simulations are performed on ODIN AUV, and the simulation results demonstrate the effectiveness and feasibility of the new design.

The paper is organized as follows. AUV dynamics and problem statement are introduced in Section 2. And in Section 3, the developed adaptive fault tolerant control method and thruster reconstruction method are presented comprehensively, which are verified by simulation results in Section 4. Finally, we draw the conclusions of this paper.

2. Preliminary work and problem statement

The nonlinear AUV model subject to ocean current disturbance and