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Autonomous Underwater Vehicles; Fault Diagnosis and Tolerance Control in Stable State, A survey

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Abstract

According to different work requirements and work scenes, there are many kinds of underwater robots. With the continuous improvement of various functions, more attention is paid to the reliability of underwater vehicles, especially the manned submersible (HOV). In order to improve the ability of underwater vehicles to complete various tasks more safely and efficiently, scholars from various countries have carried out research on the thruster which is most prone to failure, and put forward many thruster fault diagnosis and fault-tolerant control methods. This paper summarizes the fault diagnosis and fault-tolerant control methods of the thruster when the underwater vehicle is hovering at a fixed point, facing the requirements of high precision and stability, and hopes to enlighten the next research direction.

Keywords

Underwater Vehicle, Fixed-point Hover, Fault Diagnosis, Fault-tolerant Control.

1. Research background of underwater vehicle

The first century is the century of the ocean, and the development and utilization of marine resources has become the focus of global competition; driven by strategic demand, marine powers are forming from advanced water surface support mother ships to manned unmanned deep-sea submersibles capable of diving 1000m to 11000m, as well as a comprehensive pedigree of detection and operation technology and equipment.

As a deep-sea vehicle, manned submersible can carry scientific and technical personnel, engineering and technical personnel, various electronic devices and mechanical equipment to the target seafloor environment quickly and accurately, and carry out efficient exploration measurement and scientific expedition tasks. it has become an important technical means and equipment for human beings to carry out deep-sea research, development and protection [1].

In recent years, with the continuous in-depth research and exploration of the rich natural resources in the ocean, there are more and more application scenes for underwater vehicles. In view of the complex marine environment and high-precision work requirements, the control requirements of underwater vehicles are increasing day by day. Hovering control of manned submersible is needed in underwater fixed-point exploration, target recognition, data acquisition, as well as installation and detection of submarine scientific research equipment. In order to ensure the smooth progress of all kinds of work, there are high requirements for the hovering control precision and stability of the manned submersible. Therefore, the research and application of fault self-diagnosis and self-repairing fault-tolerant control technology is very important [2].

Due to the complexity and unpredictability of the work in the depths of the ocean, once the manned submersible breaks down, it will not only be unable to complete the underwater task, but also bring life danger and huge losses to the researchers in the deep sea. Therefore, the research and application of fault self-diagnosis and self-repairing fault-tolerant control technology is very important [3]. Autonomous underwater vehicles and manned submersibles are both cable-less and do not have any physical connection with the mother ship. The former is highly autonomous and unmanned, while the latter is manned, but in the event of serious failure, it will threaten personal safety.

Aiming at the manned submersible during the fixed-point hovering control, a fault-tolerant control law is proposed for the sudden failure of the thruster, and the thrust of each thruster is reconstructed. it is particularly important for the manned submersible to maintain its original working state in the complex marine environment [4].

Figure 1. The' Jiaolong' HOV with Multiple thrusters

2. Research on underwater hovering Control of underwater vehicle

With the deepening of human research on the ocean, there are many aspects of research, especially in submarine topographic mapping, ocean exploration and other aspects, the underwater vehicle needs to have the ability of fixed-point hovering [5].

The hovering process of AUV underwater vehicle is from a high-speed controllable state to a hovering state with zero speed. Hover positioning system is a closed-loop control system, in which the core idea is to control the AUV to move to a specified position and keep the position and posture unchanged [6]. The difficulty of hovering control lies in that it is difficult to keep the position and posture unchanged due to the influence of external flow and its own hydrodynamic characteristics, especially the motion of the slender AUV, has many constraints, which often makes the AUV have the characteristics of large inertia and long time delay [7]. For the hovering control of underwater vehicle, there are two ideas: through buoyancy control system and through multi-thruster thrust control. In terms of the overall effect, the effect of hovering controlled by multi-thruster thrust is better.

2.1 Control hover of buoyancy control system

The basic principle of buoyancy control system: AUV buoyancy regulation system can be divided into volumetric type and gravity type. The volumetric buoyancy regulation system mainly changes the buoyancy state of AUV without changing its own weight, while the gravity buoyancy regulation system mainly changes the buoyancy state of AUV without changing its drainage volume, and realizes buoyancy regulation [8].

The realization of the control method of the buoyancy regulation system includes the control mode of injection and drainage (air discharge, pump discharge self-injection and pump discharge) [9]and the regulation mode of buoyancy regulation cabin and balanced water tank, and its working principle is similar.

The control hover of the buoyancy control system makes the UAV in the force balance state through the injection of the hovering tank-propeller module. Reference [10] puts forward the idea of hovering balance module design for the realization of hovering state. The kinematics of the hovering tank-propeller module is analyzed, and the new underwater fixed-point hovering mode and balance of UAV are studied, which can improve the fixed-point accuracy and realize the hovering point with low energy consumption and high precision. Reference [11] through the idea of modular design, a new type of hovering tank-propeller and rotor module is designed. The hover balance of two modules is studied.

During the fixed-point hovering motion of the UAV in underwater navigation, the rotor slows down the speed and adjusts the vertical displacement, then the propeller speed of the thruster is reduced, and the lateral displacement is adjusted to make the UAV in a low-speed state. In the low speed zone, the rotor module equalizes and finally stops. The change of external force caused by hovering tank work eliminates the vertical force difference and torque difference after parking, and reduces the vertical flight inertia and rotational inertia of the whole aircraft. When hovering at a fixed point, it is necessary to eliminate the deviation between the vertical direction and the fixed point displacement. Because the positioning system has high accuracy, this deviation is so small that it can be ignored. It can be eliminated only with the help of the equalization system of the UAV itself [12].

The dynamic analysis of the four-rotor structure is carried out. The analysis shows that the modular design can control the roll angle and pitch angle in a very small range, while the yaw angle can be adjusted in a large range, and the UAV underwater hover can be well balanced.

2.2 Through multi-thruster thrust control hover

The dynamic balanced hover of unmanned underwater vehicle (UUV) with multiple thrusters is realized by adding multiple thrusters to the UAV and controlling the start and shutdown of the thruster or changing the direction of the thruster by the control system.

In reference [13], a position-velocity closed-loop AUV horizontal hover control method is designed based on the heavy-duty autonomous underwater vehicle (Autonomous Underwater Vehicle, AUV) with long rotation shape. In view of the weak maneuver and slow time-varying characteristics of AUV in hovering, on the basis of distance closed-loop control, speed feedback is introduced, and the target speed is obtained through the linear combination of distance deviation and navigation speed, and then the speed of the main thruster is controlled, so as to realize the fixed-point power hover of AUV with large inertia. Compared with the traditional position closed-loop control, the hovering range is greatly reduced, and the frequent adjustment caused by inertial overshoot is improved, which fully verifies the effectiveness of the linear control method.

Similarly, in view of the large inertia and slow response of heavy-duty AUV, with large inertia and long rotary shape, which is prone to control overshoot, a position-velocity closed-loop dynamic hover linear control method is proposed in reference [14]. On the basis of the original position closed loop, the velocity measurement feedback is introduced to increase the resistance and enhance the stability of the hovering control system. Through the linear combination of the distance deviation and the speed deviation, the target speed is obtained, and it is taken as the controlled quantity, and then the main thrust speed is controlled to obtain the required thrust value, so as to realize the position deviation adjustment and power hover.

Starting from the engineering practice, the role of the controller is played in advance to compensate for the response delay of the thruster [15]. In the lake test, comparing the position closed-loop control method with the position-speed closed-loop control method, it is concluded that the improved control method can greatly improve the power hovering performance, hover accuracy and stability are obviously improved, which lays a solid foundation for underwater communication and target detection of AUV.

Taking the typical external faults of horizontal thrusters as the research object, reference [16] discusses the fault identification and fault-tolerant control of AUV thrusters. AUV has six degrees of freedom during underwater navigation, that is, propellers with fixed angles of advance and retreat, horizontal movement, submersible, roll, trim and rotation, through the analysis of the hovering process of unmanned underwater vehicle and the study of the motion in the hovering process. The longitudinal motion equation of unmanned underwater vehicle hovering is established, and the hovering process is simulated by using the simulation module Simulink in Matlab. Through the analysis of the simulation results, the basic motion law of the hovering process of the unmanned underwater vehicle is obtained. The formula (1)is Vehicle dynamics equation and the formula (2)is Kinematic equation of vehicle(2)

$$\begin{cases} (m+\lambda_{11})\dot{v}_x = -C_{xs}\dfrac{1}{2}\rho v^2 S - \Delta G\sin\theta + F_x \\ (m+\lambda_{22})\dot{v}_y + (mx_c+\lambda_{26})\dot{\omega}_z = -mv_x\omega_z + \\ \dfrac{1}{2}\rho v^2 S(C_y^{\alpha}\alpha + C_y^{\bar{\omega}_z}\bar{\omega}_z) - \Delta G\cos\theta + F_y \\ (J_{zz}+\lambda_{66})\dot{\omega}_z + (mx_c+\lambda_{26})\dot{\omega}_y = -mx_c v_x\omega_z + \\ G(y_c\sin\theta - x_c\cos\theta) + \dfrac{1}{2}\rho v^2 SL(m_z^{a}\alpha + \\ m_z^{\bar{\omega}_z}\bar{\omega}_z) + M \end{cases} \quad (1)$$

$$\begin{cases} \dot{\theta} = \omega_z \\ \dot{x}_0 = v_x\cos\theta - v_y\sin\theta \\ \dot{y}_0 = v_x\cos\theta + v_y\sin\theta \\ a = -\arctan(\dfrac{v_y}{v_x}) \\ v = \sqrt{v^2{}_x + v^2{}_y} \end{cases} \quad (2)$$

Underwater target recognition, communication and underwater docking require its ability to hover at a fixed point. Taking the underwater docking and underwater communication as the application requirements, and the precise positioning technology of AUV as the final control requirement, the reference [17] puts forward the motion analysis of the four-rotor structure hovering balance under water. The rotor module mainly adjusts the rotor speed to produce force and torque in real time according to the gyroscope's perception of balance. The influence of different parameters on hovering balance is obtained by studying the motion of rotor. The mechanical modeling of the hovering state of the whole machine [18] is carried out, the motion of the rotor is analyzed, the reverse torque produced by the rotor is obtained, and the parameters in the motion equation are adjusted according to the balance deviation perceived by the gyroscope.

The vertical displacement of the UAV is realized by balancing the vertical force and torque of the UAV through the injection and drainage of the hovering tank. The matching of propeller and rotor is equivalent to the model of four vertical thrust and one horizontal thruster, which can make the UAV move with four degrees of freedom. Through the dynamic analysis of the hovering tank and the rotor [19], it can be known that the cooperation of the two modules well balances most of the external forces, torques and unbalanced torques, so that the UAV itself is well balanced.

3. Research on Fault Detection of underwater vehicle

Different from the conventional environment, the situation of several hundred meters underwater is changeable, so it is necessary to improve the stability of underwater detection instruments to ensure that the key equipment can run smoothly in harsh environments. avoid the action delay caused by information transmission and detection delay, leading to more serious accidents [20].

The underwater vehicle field also puts forward higher automatic control requirements for its own products. Due to the limitations of underwater communication technology and working environment, operators can not effectively monitor the operation status of the aircraft at close range, so there is an urgent need to build a closed-loop control system. The sensor provides the most basic information of aircraft operation, and transmits it to the central control area in time for residual analysis. When the residual error exceeds the pre-set threshold, start the fault tolerance mechanism [21].

Therefore, the fault diagnosis technology is gradually formed and expanded, and it can effectively complete the fault diagnosis, fault alarm and fault tolerance of the system. Generally speaking, the fault diagnosis of the working state of the underwater vehicle mainly includes three aspects: the fault diagnosis of the sensor state, the fault diagnosis of the thruster state and the fault diagnosis of the safety state [22]. Several common fault forms of thrusters are divided into: driver failure, propeller motor phase breaking, propeller winding, stuck, damage and shedding, etc. [23].

There are three main fault diagnosis methods for underwater vehicles: fault diagnosis method based on analytical model, fault diagnosis method based on signal processing and fault diagnosis method based on data drive, mainly neural network fault diagnosis method [24]. Among them, rule-based and model-based fault diagnosis methods have been applied in the existing AUV platform, signal processing and neural network methods are still dominant [25]. Therefore, this chapter focuses on summarizing several data-driven fault diagnosis methods.

3.1 Fault diagnosis method based on analytic model

The model-based fault diagnosis method is generally based on the linear regression of system dynamics, which needs to establish the conventional model and fault model, and diagnose by analyzing the residual error between the model output and the real signal output [26]. This method can deeply analyze the dynamic nature of the system, easily realize real-time diagnosis, and provide direct and useful information for the next step of fault-tolerant control or fault recovery. the disadvantage is that it is difficult to obtain an accurate mathematical model, there is always model error, which is greatly affected by external interference and noise, and is easy to be misdiagnosed or missed [27].

Most of the model-based fault diagnosis methods simplify a large number of models of the variable-coupled underwater vehicle system, and it is difficult to obtain the hydrodynamic coefficient of the robot accurately, which affects the accuracy of fault diagnosis [28].

Another method of model-based fault diagnosis is consistent diagnosis. Livingstone2 is a representative system-level diagnosis engine developed by NASA (American Aeronautics and Space Administration). It is the most successful model-based diagnosis reasoning tool in aerospace field [29], and has been applied in AutoSub6000AUV in the field of underwater vehicles. However, Livingstone2 still has some defects, especially for the problems of uncertainty and evidence conflict inherent in fault diagnosis of complex systems, the robustness of the algorithm is not enough [30].

3.2 Fault diagnosis method based on signal processing

Signal-based method, that is, through the fault feature extraction of the signal collected by the AUV sensor, fault classification is carried out based on the difference between the sensor signal and the theoretical state value of AUV [31]. The signal processing method is mainly used for fault detection, but it is rarely used in fault isolation and identification. this signal-based fault diagnosis method has higher requirements for fault observer design experts. it not only requires solid signal processing technology, but also has a very in-depth understanding of the working environment of the motion characteristics of the target carrier [32]. For AUV working in deep water, its working environment is very complex and changeable. If we only rely on the off-line design fault observer of experts to detect the running state of AUV, it is easy to ignore some new faults and minor faults. In the research of fault diagnosis and identification of underwater vehicle, the fault diagnosis method based on signal processing has not been widely recognized [33].

3.3 Fault diagnosis method based on data driving

The data-driven fault diagnosis method uses statistical methods to identify the data generated by the system to locate the fault, which can be divided into two categories: supervised learning and unsupervised learning [34]. At present, the fault detection methods of AUV system based on data drive include artificial neural network [35], support vector machine [36] and Bayesian confidence network [37]. Most of these methods are supervised learning and require the data used for training to include all fault types.

[38] Established the motion characteristics of general AUV and the modeling method of motion model, proposed a dynamic modeling method of AUV based on improved Elman neural network, and analyzed the advantages of this method in the application of AUV field. The typical fault types of AUV propeller and sensor are pointed out [39], and the simulation fault types are selected as propeller winding and wear, deviation fault and open circuit fault of sensor TCM-5.Based on the AUV of "tunnel", the hWIL simulation model is established, and the fault samples of propeller and sensor are obtained through hWIL simulation. Experimental results show that this method increases AUV autonomy and robustness to a certain extent.

Aiming at the on-line monitoring of underwater vehicle propulsion system, a fault diagnosis method of propulsion system with online learning ability is proposed in reference [40]. By analyzing the changing trend of correlation, the time delay of propulsion system is estimated online. Using the data collected during the operation, the relationship between control quantity and rotational speed is modeled on-line. In order to improve the accuracy of modeling, particle swarm optimization algorithm is used to optimize the order of the model and the amount of modeling data online [41]. In order to adapt to the changes of the environment and the state of the system during the operation, an online update mechanism of the model is designed. Based on the online update mechanism, an adaptive fault detection method which does not depend on the traditional threshold is proposed. The effectiveness of the proposed algorithm is verified by sea test data and pool tests.

A fault diagnosis method of underwater vehicle propulsion system with online learning and adaptive ability is proposed in reference [42]. In this method, the speed model of the thruster is established online based on the data, the model structure and modeling data are optimized on-line in the modeling process, and the model is updated online when the model residual becomes larger. This method has a strong adaptability to the changes of the working environment and the system itself, and does not need the mathematical model of the underwater vehicle and the detailed information of the system, and does not need off-line training. In addition, the method also identifies the control delay of the propulsion system on-line, which is helpful to improve the modeling accuracy in the case of uncertain time delay, and further improve the adaptive ability and practicability of the algorithm.

Most of the thrusters are diagnosed as two extreme modes of complete normal and complete fault, which is quite different from the actual operating condition of the underwater vehicle [43]. For the common external surge and failure failure modes of the thruster, in fact, the degree of surge and blockage is continuous and uncertain, which is related to the running state and environment of the underwater vehicle at that time. Therefore, it is not appropriate to set it to two states of complete normal and complete failure of the thruster, and several fixed fault states are applied to express it, although it is close to the actual situation, but there is still a certain distance.

In view of this, a fault pattern recognition algorithm for unmanned underwater vehicle thruster based on self-organizing SOM (Self-organizing feature Map) neural network is proposed in reference [44]. The magnitude of (jammed) fault of underwater vehicle thruster is expressed by one-range constraint coefficient iS. At the same time, thruster faults are divided into four operation modes: normal (1S1), general inrush (2S~0.5), severe surge (3S~0.25) and complete failure (4S~0). The pattern recognition of fault state is carried out by using self-organizing neural network, and some diagnostic results are obtained.

$$\overline{u} = \overline{B}_w^{+}\overline{\tau}_d = (W^{-1}\overline{B}^T(\overline{B}W^{-1}\overline{B}^T)^{-1})\overline{\tau}_d \qquad (3)$$

And the $\overline{B}_w^{+}$ $\overline{B}$ is the pseudo inverse weight matrix of propeller configuration matrix.

Neural network information fusion technology is used to improve the accuracy and real-time of on-line fault identification to solve the problem of propeller time-varying fault identification. Moreover, the fault-tolerant control signal during fault reconstruction is reconstructed by intelligent constraint optimization algorithm, so as to reduce the fault-tolerant error of the system and solve the "drive saturation" problem of conventional pseudo-fault-tolerant thrusters [45].

Considering the over-fitting and dimension explosion of shallow network in solving strong nonlinear problems, a fault diagnosis method of AUV thruster based on D-SAE deep network is proposed in reference [46]. The core idea of D-SAE algorithm [47] is the idea of self-coding, which uses artificial noisy input samples to fit the original samples to increase the robustness of the network, which is very suitable for AUV systems with many external disturbances. In the process of training, dropout algorithm is added to improve the ability of network structure to resist overfitting problems. Through the comparison of several groups of comparative experiments, it is proved that the proposed fault diagnosis method of AUV thruster based on D-SAE network has higher calculation speed and diagnosis accuracy.

When the local features of AUV sensor fault signals have important information, only by increasing the number of neurons in the hidden layer of the network to improve the ability of the network to extract fault features, it is easy to cause network dimension disaster and over-fitting phenomenon [48]. In order to solve the above problems, reference [49] proposed a CDFL algorithm structure [50] with local shift ability and relatively short training time for fault diagnosis of AUV sensors. The basic structure of the CDFL network proposed in this paper is a CNN network with convolution layer and pooling layer, which is characterized in that the filter weights in the convolution layer are trained by an external BP network [51], and do not change its value in the subsequent back propagation of the whole CDFL network to ensure its local recognition ability. Through the comparison of several groups of comparative experiments, it is verified that the AUV sensor fault diagnosis method based on CDFL network has higher calculation speed and diagnosis accuracy.

4. Research on Fault-tolerant Control of underwater vehicle Propulsion

The fault-tolerant control of the thruster of the underwater vehicle is mainly aimed at how to reconstruct the control matrix of the thruster system when the robot has controllable faults (such as partial congestion failure), so as to ensure that the underwater vehicle is in the set working state. This chapter mainly discusses the reconfiguration strategy of AUV control matrix when the fault size is known [52].

The main methods of fault-tolerant control law reconstruction of underwater vehicle can be summarized as follows: off-line design of thruster control matrix, sliding mode reconstruction of fault-tolerant control law, pseudo-inverse reconstruction of thruster control matrix and neural network control method [53].

In recent years, data-driven fault diagnosis method is combined with network neural control method. The system is divided into two independent fault-tolerant subsystems to deal with thruster and sensor faults respectively. The thruster subsystem is composed of fault detection and fault isolation. The fault-tolerant control algorithm is realized by deleting the vector of the fault thruster corresponding to the control matrix, and the redundant thruster is used to tolerate the fault of the thruster [54]. This method solves the problem of thruster redundancy and enables AUV to gradually return to the desired space trajectory of the mission in the event of a failure.

4.1 Online scheduling method for off-line design of thruster control matrix

[55] Designs a thruster control matrix off-line for thruster faults. After the corresponding faults are detected online, the corresponding arrays of control matrices are eliminated to realize the fault-tolerant control of unmanned underwater vehicles. The main deficiency of this control law reconstruction method is that firstly, the system faults must be accurately detected, and secondly, various fault modes must be known in advance, and there is nothing they can do about unknown fault modes. This simple control algorithm can only achieve limited fault tolerance.

In reference [56], the fault-tolerant system of unmanned underwater vehicle is divided into two subsystems, which deal with the faults of sensor and thruster respectively, and the fault-tolerant strategy of eliminating the corresponding vector of fault thruster control matrix is adopted in fault-tolerant control. only the extreme fault mode of complete failure of the thruster is considered, and the fault-tolerant control of the underwater vehicle is realized in a certain range.

4.2 Sliding mode reconstruction method of fault-tolerant control law

Variable structure sliding mode control method [57], which uses sliding mode control technology to reconstruct control law on the basis of fault identification. The design method of sliding mode fault tolerant control for autonomous underwater vehicle (AUV) is proposed in reference [58]. The factors affecting the control performance of AUV are analyzed, and the adaptive sliding mode control method is applied to the depth control of AUV. It can maintain stable and satisfactory performance under various interference conditions. The model of the system is obtained by the method of system identification, and then the synovial control quantity is modified by the identified model.

4.3 Pseudo-inverse reconstruction method of thruster control matrix

Pseudo-inverse algorithm of control matrix reconstruction matrix pseudo-inverse reconstruction method is one of the most commonly used control law reconstruction algorithms for underwater vehicles. Pseudo inverse matrix is a special case of general inverse matrix. although the calculation is simple, in many practical applications, because there is a maximum speed of the motor, its control solution is difficult to meet the constraints of the control voltage of the underwater vehicle thruster. As a result, the pseudo-inverse reconstruction method can only be used in some special fault modes.

The methods of T-approximation (truncation) and S-approximation (scaling) are proposed in reference [59]. The T-approximation is to truncate any control vector element that is out of the constraint condition, while the S-approximation is to keep the control voltage within the constraint range by scaling out the pseudo-inverse reconstruction solution. However, in many practical applications, its control solution is difficult to meet the constraints of the control voltage of the underwater vehicle thruster, so the pseudo-inverse reconstruction method can only be used in some special fault modes.

An online pseudo-inverse fault-tolerant control strategy is proposed in reference [61], which makes the fault-tolerant control of AUV thruster closer to the actual running state of the system, and improves the application range and control performance of fault-tolerant control. The reference [62] sets that once the thruster fails, it is assumed that it fails completely, and the corresponding vector of the fault thruster is deleted completely, so as to achieve the fault-tolerant control strategy. Although the results show that the controller and fault-tolerant control strategy can achieve better control accuracy, the problem of thruster control saturation and the degree of fault are not considered.

In order to ensure that the intelligent underwater vehicle (AUV) can successfully complete the corresponding tasks at a certain depth even if some of the motion actuators fail, a fault-tolerant motion control strategy with fixed depth is proposed in reference [63]. Aiming at the fault of the vertical thruster of a certain intelligent underwater vehicle, the control strategy is designed and implemented from a practical point of view, based on the idea of reconfigurable fault-tolerant control and combined with the (ADRC) method of auto-disturbance rejection control [64]. The control strategy includes two kinds of fixed depth controller design, which are vertical push normal working condition and vertical push fault control respectively, trying to rely on the relevant fault information to achieve fault tolerant control through reconfiguration replacement. The results show that the fixed-depth fault-tolerant control strategy based on reconfiguration fault-tolerant control idea and auto-disturbance rejection control method is not only effective, but also has better interference suppression, which can provide better control effect for the robot.

4.4 Neural network control method

A comprehensive fault-tolerant control scheme for nonlinear multi-fault systems is proposed in reference [65]. After using fuzzy credit allocation CMAC to estimate unknown faults online, sliding mode control algorithm and CMAC cerebellar fault identification are combined. An effective control law reconstruction strategy based on sliding mode control technology is adopted to compensate for the influence of multiple faults. Aiming at multiple fault scenarios and three-tank system (three-tank system) [67], the controller adjusts the control signal to ensure the stability of the system by adding correction sliding mode control signal. Numerical simulation shows the effectiveness of the controller. Compared with the conventional pseudo-inverse reconstruction method, the neural network control method not only saves the unnecessary secondary approximation, but also improves the fault-tolerant control effect obviously [68]. In order to overcome the defect of pseudo-inverse reconstruction algorithm of AUV control law reconstruction, that is, the problem of fault-tolerant control error caused by control signal saturation.

In reference [69], in order to solve the problem of reliability control of underwater vehicle under thruster congestion, genetic algorithm is introduced into the reconstruction of fault-tolerant control law, and a reconstruction method of fault-tolerant control law of underwater vehicle with constraint genetic algorithm is proposed. In different fault cases, the relevant fault weight matrix is given, the genetic algorithm is used to find the optimal solution of the control matrix, and the control matrix of the thruster is reconstructed. Compared with the pseudo-inverse reconstruction method of control matrix, the control quantity obtained does not need to go through truncation approximation or scaling approximation, so as to avoid the error caused by truncation or scaling approximation. simulation results show the effectiveness of the proposed control law reconstruction algorithm.

[70] Studied the fault-tolerant control method for the trajectory tracking of manned submersible that can continue the trajectory tracking mission in the case of propeller failure in consideration of possible propeller failure during the trajectory tracking control of the deep-Sea Warrior manned submersible. On the basis of the design of heading priority fault tolerance, the improved quantum particle swarm optimization algorithm is combined with the traditional pseudo-inverse fault-tolerant control method. a hybrid fault-tolerant scheme and the corresponding fault-tolerant control algorithm are proposed for different types of thruster faults.

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