# Distirbuted Fault Detection of Multiple Unmanned Ships Based on Fuzzy Model

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***Abstract*—This paper proposes a distributed fault detection scheme for Multiple Unmanned Surface Vehicle Systems (MUSVSs) based on a fuzzy model. Initially, the dynamic equations of unmanned surface vehicles (USVs) are presented. Considering the communication topology among the USVs and potential thruster failures, T-S fuzzy models incorporating fault information for each unmanned surface vehicle in the MUSVS are developed. Subsequently, an observer is designed for each USV to generate a residual signal, capable of utilizing measurement information not only from the current USV but also from neighboring USVs and their corresponding observers. Additionally, a fault reference model is employed to enhance the performance of the fault detection system. A fuzzy Lyapunov function-based method and an inverse convex approach are developed, along with the introduction of a free-weighting matrix method to ensure that the obtained sufficient conditions guarantee the asymptotic stability of the fuzzy fault detection system, as well as $H_\infty$ performance. However, the constructed matrix inequalities contain coupling terms, which hinder the direct design of the observer, necessitating the construction of corresponding solvability conditions. Finally, a multi-agent system consisting of four USVs is established for simulation verification. In the simulation, the LMI toolbox in MATLAB is used to solve the constructed matrix inequalities, and the gain of the designed observer is determined. By comparing the instances when the residual evaluation function exceeds the threshold, the simulation results validate the effectiveness and applicability of the proposed distributed fault detection scheme.**

***Index Terms*—Multiple unmanned surface vehicle systems, T–S fuzzy system, distributed fault detection.**

## I. Introduction

Globally, the exploration and utilization of marine resources are increasingly emphasized, and unmanned surface vehicle (USV) systems, with their efficiency, flexibility, safety, and low cost, are gradually becoming essential tools for maritime operations. In recent years, inspired by the collective behavior of natural organisms, the theory of multi-robot cooperative control has developed rapidly. With continuous advancements in robotics, communication and navigation, artificial intelligence, and computer technologies in the field of USV motion control, multi-USV systems have integrated the advantages of swarm intelligence and the high autonomy of individual USVs, addressing the limitations of single-vessel capabilities. During formation sailing, multi-USV systems form dynamic networks for information exchange, effectively enhancing operational efficiency, system fault tolerance, and defense against sudden attacks, thereby ensuring the successful completion of missions.Compared to single vessels, multi-USV systems exhibit stronger robustness and communication capabilities, higher maneuverability, flexibility, and operational efficiency, as well as a broader operational range. Numerous advancements have been made in multi-USV systems, such as formation control and obstacle avoidance control. For instance, in literature [1], a formation control model based on deep reinforcement learning was developed using a virtual leader method. The model sets a reward function based on the difference between the actual speed and angle of each USV and the desired speed and angle, ensuring that the higher the reward function value, the smaller the formation error, thus maintaining the stability of the USV formation. In literature [2], an improved traditional artificial potential field method was proposed, where global artificial potential field target points were allocated to sub-target points along different paths and distributed to the USV group to deploy formation trajectories. Literature [3] proposed a distributed guidance vector field controller for a cross-domain unmanned system consisting of heterogeneous unmanned aerial vehicles and USVs to achieve cooperative navigation while maneuvering along its designated path. Literature [4] presented an adaptive null-space-based (NSB) behavior method to address the issues of saturation planning and adaptability in traditional NSB methods when applied to multi-USV formation control.

However, since USVs operate in complex and dynamic marine environments, they are susceptible to adverse natural conditions (such as wind, waves, tides, and weather changes) as well as the inherent complexity of the system and extended periods of operation. These factors make the USV system prone to failures during mission execution. For multi-USV systems, communication networks are used to exchange information between USVs to achieve coordinated cooperation. When one USV encounters a failure, the fault information could potentially be transmitted across the entire USV system. Therefore, if a fault in the USV system is not detected and resolved promptly, it could lead to system failure and mission failure, resulting in significant economic losses. Hence, research on fault detection algorithms for multi-USV systems is of great importance. Currently, there have been numerous advancements in fault detection algorithms for multi-agent systems. Literature [5] investigates the problem of distributed fault detection in multi-agent systems and proposes a fault detection method based on a reduced-order unknown input observer. By constructing a reduced-order unknown input observer in one agent, it is possible to detect faults in its neighboring agents. Literature [6] studies the fault detection and estimation problem of the physical layer network in cyber-physical systems under unknown external disturbances. A distributed fault detection observer is constructed for each physical layer node based on adaptive threshold methods and sliding mode observer methods to detect actuator faults.

However, the complex external influences on USVs, coupled with the nonlinear coupling between the multi-degree-of-freedom motions, often result in nonlinear models for USVs, posing challenges to the research on multi-USV systems. Most of the existing fault detection algorithms for multi-agent systems are based on linear systems, while there are relatively few achievements in detection algorithms for non-linear systems. In fuzzy control theory, the Takagi-Sugeno (T-S) fuzzy model has been proposed as a powerful tool for addressing control problems in nonlinear systems. For complex large-scale nonlinear systems, the T-S fuzzy model integrates multiple linear subsystems through If-Then rules to approximate the dynamic characteristics of nonlinear systems. This advantage allows various linear control theories to be effectively applied to the control of nonlinear systems. Using the T-S fuzzy model, many fuzzy control methods have been successfully applied to nonlinear ship steering systems, achieving excellent control performance. Literature [7] investigated the dynamic positioning control problem of nonlinear USV systems under network communication constraints and denial of service attacks. Literature [8] developed a fuzzy controller design method for multi-ship steering systems to achieve formation and encirclement objectives. The Takagi-Sugeno fuzzy model was used to describe the behavior of each ship in a multi-ship steering system with a leader-follower structure. A fuzzy formation and containment controller was developed using the parallel distributed compensation design method. However, in the existing literature, T-S fuzzy models for USV systems are almost exclusively used for controller design, often for a single USV, with few studies focusing on fault detection algorithms. Of course, there are also fault detection algorithms based on fuzzy models. For example, literature [9] studied the fault detection filtering problem for nonlinear dynamic systems under the Takagi-Sugeno fuzzy framework. Literature [10] investigated the design of event-triggered fault diagnosis filters for nonlinear networked control systems with simultaneous sensor and process faults. However, most of the existing literature on fault detection algorithms is based on single systems and has not been applied to USV systems.

Based on the above discussion, this paper develops a distributed fault detection algorithm for multi-USV systems. First, a three-degree-of-freedom USV dynamic model is considered and extended to a homogeneous multi-agent system. Then, the fixed communication topology among the multiple USVs and the network delays in information transmission are considered, and the T-S fuzzy model of the USVs is obtained by incorporating the dynamic model. Next, an observer is constructed for each USV to generate residual signals. This observer not only receives measurement information from the current USV but also receives information from neighboring USVs and the observers constructed on those neighboring USVs. Additionally, a fault reference model is adopted to enhance the performance of the fault detection system. On this basis, methods based on the fuzzy Lyapunov function and inverse convex method are developed, and a free-weighting matrix is introduced to perform the stability analysis of the fault detection system. The obtained sufficient conditions ensure that the fuzzy fault detection system is asymptotically stable and has a specified $H_\infty$ disturbance attenuation level against disturbances and faults. The main contributions of this paper are as follows:

(1) A multi-USV model based on the T-S fuzzy model representation is constructed, considering the communication delays between USVs. It is proven that the distributed fault detection system is asymptotically stable and has a specified $H_\infty$ disturbance attenuation level.

(2) The parameter coupling issue in the stability conditions is addressed, and a design scheme for the fault detection observer based on the LMI (Linear Matrix Inequality) method is developed.