Fault-Tolerant Control of Multi-USV Systems Based on Fuzzy Systems

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***Abstract*—Multi-Unmanned Surface Vehicle Systems (Multi-USV Systems) play an increasingly important role in modern marine missions, widely applied in ocean monitoring, environmental protection, resource exploration, and military tasks. However, the complexity of the marine environment and the inherent risks of these missions pose significant challenges to the system, including unforeseen system failures, communication interruptions, and uncertainties brought by dynamic environments. These challenges can lead to partial or complete system failure, severely impacting the successful completion of missions. Therefore, designing an adaptive and robust fault-tolerant control strategy to ensure that Multi-USV systems can remain stable and efficient in the event of a failure has become a key research issue. This paper proposes a fault-tolerant control method based on fuzzy systems, utilizing the powerful reasoning capabilities of fuzzy logic and its advantage in handling uncertain information. This method can detect faults in real-time and take effective control actions to ensure system stability and mission continuity when critical components of the system fail. By designing reasonable fuzzy rules and inference mechanisms, the proposed strategy can achieve effective fault-tolerant control of complex Multi-USV systems without relying on precise mathematical models. Simulation and experimental results demonstrate that the proposed method exhibits significant robustness in dealing with various failure scenarios, significantly improving the mission success rate of Multi-USV systems under faulty conditions.**

***Index Terms*—Multi-USV Systems, Fault-Tolerant Control, Fuzzy Systems, Autonomous Surface Vehicles, Distributed Control**

I. Introduction

In the context of current technological advancements, the exploration and utilization of marine resources have gradually become a global focal point. However, the complex and dynamic marine environment poses significant challenges to traditional marine operations. As an emerging technological approach, Multi-Unmanned Surface Vehicle Systems (Multi-USV Systems) have gradually replaced traditional manned systems due to their high efficiency, flexibility, and low cost, becoming a mainstay in ocean exploration, environmental monitoring, resource surveying, marine scientific research, and military defense. However, the widespread application of Multi-USV Systems also brings new technical challenges, especially in dealing with high uncertainties and unpredictability in the marine environment, which impose higher demands on the system's stability, reliability, and fault-tolerance.

In practical applications, Multi-USV Systems often need to autonomously perform tasks in harsh marine environments far from shore-based control. The characteristics of this environment mean that the system may encounter various unforeseen failures and challenges during task execution, such as strong waves, severe weather conditions, complex underwater terrain, and possible underwater obstacles. Additionally, factors such as the instability of wireless communications, errors in the navigation system, and delays or failures in sensor data can severely threaten the normal operation of the system. In such high-risk operational environments, traditional control strategies, which heavily depend on the system's operating environment and system state, often struggle to cope with these unexpected situations. Therefore, designing a fault-tolerant control strategy that can adapt to environmental changes and internal system failures is crucial to ensuring the safe and efficient operation of Multi-USV Systems.

Fault-tolerant control refers to the ability of a system to maintain its functionality and performance despite the occurrence of component failures. This strategy is particularly crucial in key applications of Multi-USV Systems, such as continuous ocean monitoring and military reconnaissance missions. In these tasks, the failure of any USV could lead to the failure of the entire mission or cause serious consequences. Therefore, designing an efficient fault-tolerant control strategy that not only detects and diagnoses faults in real-time but also adjusts the system's control strategy to maintain stable operation under faulty conditions is essential for improving the overall robustness and mission success rate of Multi-USV Systems.

Fuzzy systems, as a powerful tool for handling uncertainty and fuzzy information, have been widely applied in the field of fault-tolerant control. The key advantage of fuzzy systems lies in their ability to effectively control complex systems without relying on precise mathematical models, which is particularly important for complex, multi-variable systems like Multi-USV Systems. In the control of Multi-USV Systems, fuzzy systems can utilize expert knowledge and experience to define a series of fuzzy rules, and through an inference mechanism, evaluate the system state in real-time. Upon detecting a system failure, they can quickly respond by adjusting the fuzzy control parameters. This allows the system to flexibly adapt to environmental changes and internal system failures, thus ensuring system stability and mission continuity.

Moreover, the distributed nature of Multi-USV Systems means that each USV must not only complete its assigned tasks independently but also collaborate with other USVs. Therefore, in the design of fault-tolerant control strategies, it is necessary to consider not only the fault-tolerance of individual USVs but also the coordination and control strategy of the entire system. Once a USV fails, other USVs should be able to receive relevant information through the communication network and quickly adjust their control strategies to compensate for the mission gap caused by the failed USV, ensuring the stability of the overall system and the smooth completion of the mission.

In summary, this paper proposes a fault-tolerant control strategy for Multi-USV Systems based on fuzzy systems. This strategy not only detects and diagnoses system failures in real-time in complex marine environments but also adjusts the system control strategy through fuzzy logic reasoning and control rule adjustment to maintain system stability and mission execution capability under failure conditions. The research presented in this paper not only has significant theoretical implications but also provides strong technical support for the practical application of Multi-USV Systems in complex marine environments. Simulation and experimental validation demonstrate that the proposed fault-tolerant control strategy exhibits good robustness and adaptability in dealing with various failure scenarios, further proving its effectiveness in improving the overall performance of Multi-USV Systems.

II. Structure of Multi-USV Systems

The basic structure of a Multi-USV System consists of multiple USVs that exchange information and collaborate through a wireless communication network. Each USV is typically equipped with subsystems such as a navigation system, attitude control system, communication system, propulsion system, and mission execution system. The coordinated operation of these subsystems determines the task execution capability of the entire Multi-USV System.

A. Navigation System

The navigation system is responsible for the position awareness and path planning of the USV. In a marine environment, the navigation system typically utilizes GPS, Inertial Navigation Systems (INS), and marine environment sensors to obtain precise position and motion information. The navigation system is critical to ensuring that the USV follows a predetermined trajectory, but it is also susceptible to environmental interference and hardware failures.

B. Attitude Control System

The attitude control system is responsible for the stability and maneuverability of the USV, ensuring that the USV remains balanced and executes precise motion commands under complex sea conditions. This system usually consists of gyroscopes, accelerometers, and rudders, and its operating status directly affects the controllability of the USV.

C. Communication System

The communication system is a crucial component of Multi-USV Systems, responsible for the exchange of information between USVs and with the shore-based control center. The stability of the communication system determines whether the USVs can effectively collaborate. However, the complexity of the marine environment, such as electromagnetic interference and signal attenuation, can lead to communication interruptions or delays, affecting the overall operation of the system.

D. Propulsion System

The propulsion system provides the energy needed for the USV's movement, typically consisting of engines, batteries, and thrusters. The reliability of the propulsion system is critical to the USV's endurance and motion control, and any failure in the propulsion system could result in the USV being unable to continue its mission.

E. Mission Execution System

The mission execution system includes various sensors and actuators used to accomplish specific mission requirements, such as underwater exploration, target recognition, and environmental monitoring. The performance of the mission execution system is directly related to whether the Multi-USV System can successfully complete its tasks.

During the actual operation of the Multi-USV System, any of the above subsystems may fail due to various reasons, such as hardware aging, environmental impacts, or operational errors. These failures not only affect the operation of individual USVs but may also propagate through the communication network, leading to the failure of the entire system. Therefore, designing a fault-tolerant control strategy that can detect and respond to these failures in real-time is essential to ensuring the stability and reliability of the system and the successful completion of missions.