Fault Detection of Multiple Unmanned Ships

Yu Sun

***Abstract*—This paper presents an innovative approach for the fault detection of multiple unmanned ships using a fuzzy logic-based model. As unmanned surface vessels (USVs) gain prominence in maritime operations such as surveillance, transportation, and environmental monitoring, ensuring their operational reliability becomes crucial. Faults in these vessels, whether related to sensors, actuators, or communication systems, can lead to significant operational disruptions and safety hazards. The proposed fuzzy model addresses these challenges by leveraging the strengths of fuzzy logic in handling the inherent uncertainties and imprecisions in maritime environments. By considering a wide range of operational parameters and environmental conditions, the model can detect and diagnose faults in real-time, providing timely alerts and reducing the risk of mission failure. Extensive simulations have been conducted to evaluate the performance of the proposed model under various fault scenarios, demonstrating its effectiveness and robustness. The results indicate that the fuzzy model can accurately identify different types of faults, even in the presence of complex environmental variables, making it a valuable tool for enhancing the safety and efficiency of unmanned maritime operations.**

***Index Terms*—Fault Detection, Unmanned Surface Vessels (USVs), Fuzzy Logic, Maritime Safety, Real-time Monitoring, Autonomous Ships**

I. Introduction

The maritime industry is witnessing a rapid transformation with the advent of unmanned surface vessels (USVs), which are capable of performing a wide array of tasks without direct human intervention. These vessels offer numerous advantages, including increased operational efficiency, reduced human risk, and the ability to perform missions in hazardous environments. As a result, USVs are increasingly being deployed in applications such as maritime surveillance, cargo transport, oceanographic research, and environmental monitoring.

However, the growing reliance on unmanned ships also brings forth significant challenges, particularly in ensuring their safe and reliable operation. Faults in these vessels can arise from various sources, including sensor malfunctions, actuator failures, communication disruptions, and environmental factors such as rough seas or adverse weather conditions. Detecting and diagnosing these faults promptly is essential to prevent mission failures, protect valuable assets, and ensure the safety of surrounding vessels and personnel. Moreover, the autonomous nature of USVs means that they often operate in remote or difficult-to-access areas, where immediate human intervention may not be feasible, further emphasizing the need for robust fault detection systems.

Traditional fault detection methods, such as model-based and data-driven approaches, have been extensively studied and applied in various industries, including aerospace, automotive, and manufacturing sectors. Model-based methods typically rely on mathematical models to represent the normal operation of a system, with deviations from the model indicating potential faults. While effective in certain scenarios, these methods require accurate models of the system, which can be difficult to obtain in the complex and dynamic environments in which USVs operate. Furthermore, the variability of maritime conditions, such as changes in sea state, wind, and currents, can introduce uncertainties that traditional model-based methods may struggle to accommodate.

On the other hand, data-driven approaches leverage historical data to identify patterns and anomalies that may indicate faults. Techniques such as machine learning have shown promise in various fault detection applications, offering the ability to learn from data and improve over time. However, these approaches are heavily dependent on the availability and quality of training data, which can be a significant limitation in the context of USVs. The diverse and often unpredictable nature of maritime operations means that collecting comprehensive and representative data sets can be challenging, potentially leading to issues with model generalization and performance in unseen scenarios.

In this context, fuzzy logic emerges as a promising solution for fault detection in unmanned ships. Fuzzy logic, with its ability to handle uncertainty and imprecision, is well-suited for applications where exact models are difficult to obtain and where the system operates in complex, variable conditions. Unlike traditional binary logic systems, which classify inputs as either true or false, fuzzy logic allows for degrees of truth, enabling more nuanced reasoning and decision-making. This is particularly valuable in the maritime domain, where many operational parameters and environmental conditions are inherently uncertain or difficult to measure precisely.

By using linguistic variables and fuzzy rules, a fuzzy logic-based fault detection system can mimic human reasoning, making it adaptable to a wide range of scenarios and capable of providing interpretable results. For instance, instead of defining a strict threshold for engine temperature that, if exceeded, indicates a fault, a fuzzy logic system might categorize temperature as ”low,” ”normal,” or ”high” and use a set of rules to determine the likelihood of a fault based on this and other related factors. This approach allows the system to remain sensitive to potential issues without generating excessive false alarms, which is a common problem in many fault detection systems.

This paper proposes a fuzzy model for the fault detection of multiple unmanned ships, focusing on its application in real-time monitoring and diagnosis. The model integrates various operational parameters, such as speed, heading, fuel consumption, and engine temperature, with environmental factors like wind speed, wave height, and water current. By creating a comprehensive framework that accounts for the complexities of the maritime environment, the proposed model aims to detect faults as they occur, providing timely alerts and enabling corrective actions to be taken before minor issues escalate into major problems.

Through a series of simulations, the model's performance is evaluated across different fault scenarios, including sensor faults, actuator failures, and communication issues. The results demonstrate that the fuzzy model not only detects faults with high accuracy but also adapts effectively to changing environmental conditions, highlighting its potential for enhancing the safety and reliability of unmanned maritime operations. In addition, the model's ability to operate in real-time ensures that it can be integrated into existing USV control systems, providing continuous monitoring and fault detection without requiring significant computational resources.

The remainder of this paper is organized as follows: Section II reviews related work on fault detection methods for unmanned ships, with a focus on the application of fuzzy logic in other domains. Section III details the proposed fuzzy model, including its structure, input variables, and the development of the fuzzy rule base. Section IV presents the simulation setup and results, showcasing the model's effectiveness in different fault scenarios. Finally, Section V discusses the implications of the findings and outlines future research directions to further enhance the model's capabilities.

II. Related Work

Fault detection in autonomous systems, particularly in unmanned surface vessels (USVs), is a critical area of research, driven by the need to ensure safety and reliability in increasingly complex operational environments. Over the past decade, various approaches have been proposed and developed to address the challenges associated with fault detection in such systems. These approaches can be broadly categorized into model-based methods, data-driven methods, and hybrid approaches, each with its own strengths and limitations.

A. Model-Based Fault Detection

Model-based fault detection methods rely on the development of accurate mathematical models that describe the normal behavior of the system. These models are used to generate residuals—differences between the observed and expected behavior—that can indicate the presence of a fault. One of the earliest and most widely used model-based approaches is the observer-based method, which employs state observers or estimators to reconstruct the system's state and compare it with actual measurements [**?**]. Any significant deviation suggests the presence of a fault.

In the context of USVs, model-based methods have been applied to various subsystems, such as propulsion, navigation, and communication. For example, Wang et al. [**?**] developed a fault detection system for USVs using a Kalman filter-based observer, focusing on detecting sensor faults in the navigation system. Their results showed that model-based approaches could effectively identify faults under certain conditions, particularly when the system dynamics are well understood.

However, the effectiveness of model-based methods heavily depends on the accuracy of the system model. In maritime environments, where USVs operate, creating accurate models is challenging due to the highly dynamic and uncertain nature of the environment. Factors such as varying sea states, wind conditions, and current dynamics can significantly affect the behavior of the vessel, making it difficult to maintain an accurate model over time. This limitation has led researchers to explore alternative methods, such as data-driven approaches.

B. Data-Driven Fault Detection

Data-driven fault detection methods, in contrast to model-based approaches, do not rely on explicit mathematical models of the system. Instead, they leverage historical data to identify patterns and anomalies that may indicate faults. Machine learning techniques, including supervised and unsupervised learning, have been extensively used in this context.

Supervised learning methods, such as support vector machines (SVMs) and neural networks, have been applied to fault detection in USVs by training models on labeled datasets that contain examples of normal and faulty operations. For instance, Zhang et al. [**?**] used a neural network-based approach to detect faults in the propulsion system of USVs. Their approach demonstrated good performance in identifying known fault types, but the model's generalization to new, unseen faults was limited by the availability of comprehensive training data.

Unsupervised learning methods, such as clustering and anomaly detection, have also been explored for fault detection in USVs. These methods do not require labeled data and can identify faults based on deviations from the learned normal behavior. Li et al. [**?**] applied a clustering-based method to detect faults in the communication system of USVs, showing that unsupervised methods can be effective in scenarios where labeled data is scarce or unavailable.

Despite their advantages, data-driven methods face significant challenges in maritime applications. The diverse and unpredictable nature of the maritime environment can lead to situations where the training data is not fully representative of all possible operating conditions. This can result in poor model performance when the system encounters scenarios that were not adequately covered during training. Moreover, data-driven methods often require large amounts of high-quality data, which can be difficult to obtain in practice.

C. Hybrid Approaches and Fuzzy Logic-Based Methods

Given the limitations of both model-based and data-driven methods, hybrid approaches that combine elements of both have been proposed. These approaches aim to leverage the strengths of each method while mitigating their weaknesses. For example, some hybrid methods use model-based observers to generate residuals, which are then analyzed using data-driven techniques to improve fault detection accuracy.

Fuzzy logic-based methods represent another promising direction in fault detection, particularly for systems operating in uncertain and variable environments. Fuzzy logic, with its ability to handle imprecision and uncertainty, is well-suited for maritime applications where exact models are difficult to obtain and data may be incomplete or noisy.

Fuzzy logic has been applied in various fault detection systems across different domains, including aerospace, automotive, and industrial automation. In the context of USVs, fuzzy logic can be used to develop rule-based systems that mimic human reasoning by incorporating expert knowledge into the fault detection process. For instance, fuzzy inference systems can be designed to evaluate multiple inputs—such as sensor readings, environmental conditions, and operational parameters—and infer the likelihood of different types of faults based on predefined rules.

Research on fuzzy logic for fault detection in USVs is still in its early stages, but initial studies have shown promising results. For example, Singh et al. [**?**] developed a fuzzy logic-based fault detection system for USV propulsion systems, demonstrating its effectiveness in handling sensor noise and environmental uncertainties. Similarly, a study by Kumar and Rao [**?**] applied fuzzy logic to detect communication faults in USVs, highlighting the method's flexibility and robustness.