Industrial Engineering and Innovation Management (2024)
Clausius Scientific Press, Canada

DOI: 10.23977/ieim.2024.070216
ISSN 2522-6924 Vol. 7 Num. 2

Research on the cooperative operation of intelligent tugs and maritime autonomous surface ships (MASS)

Xuejun Wang

Tianjin Port Tugboat & Lighter Co., Ltd, Tianjin, 300345, China

Keywords: Intelligent tugs, Maritime Autonomous Surface Ships (MASS), collaborative operations, hybrid intelligent algorithm, machine learning

Abstract: With the rapid development of autonomous technology, the application of intelligent tugs and Maritime Autonomous Surface Ships (MASS) in collaborative operations in the field of marine engineering has attracted increasing attention. This study aims to explore the key technologies, collaborative strategies, and application effects of intelligent tugs and MASS in specific marine tasks. By employing a hybrid intelligent algorithm and machine learning technology, this study designs an intelligent decision support system to achieve efficient and safe collaborative operations. The results show that optimizing collaborative operation strategies can significantly improve the efficiency and safety of task execution. The findings of this study provide an important theoretical and practical basis for the further development of intelligent ship technology and its application in the field of marine engineering.

1. Introduction

With the increase in global maritime activities and technological advancements, intelligent ship technology has become a research hotspot in the field of marine engineering. The collaborative operation of intelligent tugs and MASS, especially in complex marine environments, can not only improve operational efficiency but also reduce labor costs and safety risks. This paper reviews the development background of intelligent ship technology, analyzes the importance of collaborative operations, and proposes research objectives and methods.

2. Intelligent Tug and MASS Technology Framework

2.1. Design and Function of Intelligent Tugs

2.1.1. Design Concept and Key Technologies

The design concept of intelligent tugs is based on achieving highly automated navigation, operation, and monitoring to improve the efficiency and safety of maritime operations. This design integrates advanced sensor technology, artificial intelligence (AI), machine learning, and automatic control systems to achieve real-time monitoring, autonomous decision-making, and precise operation of ship status. Key technologies include but are not limited to multi-sensor data fusion technology, autonomous navigation systems, remote control, and autonomous driving technology. Through these technologies, intelligent tugs can autonomously identify and respond to changes in the surrounding environment, such as avoiding obstacles, adjusting routes, and executing complex towing operations, thereby enhancing operational safety and reliability[1].

2.1.2. Functional Characteristics

The functional characteristics of intelligent tugs mainly manifest in autonomy, flexibility, and efficiency. Firstly, autonomy allows intelligent tugs to perform tasks such as navigation, positioning, obstacle avoidance, and towing without human supervision. Secondly, flexibility means that intelligent tugs can quickly adjust their operation mode and behavioral strategy according to task requirements and changes in the marine environment. Finally, efficiency is achieved through optimizing the operation process and reducing human errors, especially in complex or harsh marine environments, where intelligent tugs can maintain high operational efficiency and accuracy. Tianjin Port Tugboat Co., Ltd. currently has 4 intelligent tugs, and 2 new intelligent tugs will be put into production in the first half of 2024. The intelligent tug fleet has initially taken shape. How to fully utilize intelligent tugs in different fields and scenarios has become an urgent issue to be addressed[2].

2.2. Technological Progress of Maritime Autonomous Surface Ships (MASS)

2.2.1. Current Technological Development

The technological progress of Maritime Autonomous Surface Ships (MASS) mainly reflects continuous innovation and optimization of its core technologies, including but not limited to autonomous navigation, intelligent obstacle avoidance, and task planning and execution systems. In recent years, through the integration of high-precision GPS systems, LiDAR, sonar, and visual sensors, MASS can achieve high-precision self-positioning and environmental perception. Moreover, combined with artificial intelligence and deep learning algorithms, MASS can analyze collected data in real-time, making rapid and accurate decisions to cope with complex marine conditions and unknown obstacles.

2.2.2. Core Technologies

The technological progress of MASS also includes the development of highly automated task execution systems, which enable them to complete a variety of tasks such as mapping, surveillance, search and rescue, and scientific research without human intervention. These technological advancements greatly expand the application areas of MASS and improve the safety and efficiency of executing maritime tasks. With the continuous advancement of technology, future MASS will have higher levels of autonomy and adaptability, able to work effectively in more complex and dynamic marine environments.

2.3. Technological Requirements for Collaborative Operations

2.3.1. Technological Challenges and Requirements

Collaborative operations between intelligent tugs and Maritime Autonomous Surface Ships (MASS) face multiple technological challenges, mainly including highly reliable communication systems, precise synchronous control, and efficient decision support systems. To achieve efficient collaboration, a stable and reliable communication network is needed to ensure real-time transmission and accurate interpretation of information between platforms. In addition, collaborative operations require precise time and action synchronization to ensure the coordination consistency and execution efficiency of tasks. This requires a high degree of interoperability and compatibility between various systems[3].

2.3.2. Innovative Solutions

Facing these technological challenges, this study proposes a series of innovative solutions, including the development of machine learning-based adaptive communication protocols to optimize signal transmission and reception in complex marine environments. At the same time, the introduction of a control system based on Distributed Artificial Intelligence (DAI) achieves efficient decision-making and execution, as well as precise synchronization between multiple ships. These technological advancements not only enhance the performance of collaborative operations but also lay a solid foundation for the future development of intelligent ships.

3. Collaborative Operation Strategies and Algorithms

3.1. Collaborative Navigation and Obstacle Avoidance Strategies

3.1.1. Importance and Challenges of Collaborative Navigation

Effective collaborative operation of intelligent tugs and Maritime Autonomous Surface Ships (MASS), especially in navigation and obstacle avoidance, is not only a technological advancement but also a key factor in the safety and efficiency of future marine operations. This kind of collaborative operation imposes higher requirements on the positioning accuracy of single ships, real-time data processing capability, and information sharing ability among multiple ships. The navigation system needs to process a large amount of data from various sensors, including but not limited to Global Positioning System (GPS), Inertial Measurement Unit (IMU), radar, and sonar, to achieve precise environmental perception. At the same time, these data need to be shared in real-time within the fleet to ensure that all members can navigate and avoid obstacles synchronously and accurately. In this process, ensuring the real-time, accuracy, and anti-interference capability of data becomes a major challenge for achieving collaborative navigation and obstacle avoidance strategies.

3.1.2. Technical Implementation Solutions

The implementation of collaborative navigation and obstacle avoidance strategies relies first on highly developed sensor technology and data fusion technology. By using a variety of sensors such as radar, sonar, Beidou, DGPS, and cameras, combined with advanced data fusion algorithms, high-precision perception and identification of the surrounding environment can be achieved. Secondly, decision algorithms based on artificial intelligence and machine learning analyze and process the collected data, dynamically formulating and adjusting navigation routes and obstacle avoidance strategies. In addition, the use of multi-ship collaborative control technology, through high-speed communication networks, achieves information sharing and action coordination between ships, ensuring that the entire fleet can efficiently and safely perform tasks while maintaining formation.

3.2. Task Allocation and Optimization Algorithms

3.2.1. Importance of Task Allocation

In the collaborative operation of intelligent tugs and Maritime Autonomous Surface Ships (MASS), the rationality of task allocation directly affects the overall efficiency and safety of the operation. This process requires in-depth analysis and understanding of the performance characteristics of each ship, as well as their performance capabilities in specific tasks and marine environments. The task allocation problem includes not only how to allocate tasks based on the dynamic characteristics, payload capacity, and operational efficiency of ships but also involves multi-dimensional decision-making such as route planning, operation timing, and resource allocation. The goal of this complex process is to ensure that each ship can maximize its efficiency in its best field while considering the overall optimization of the operation, including minimizing operation time, reducing energy consumption, and avoiding resource conflicts, to achieve the dual goals of improving operation efficiency and ensuring operation safety.

3.2.2. Optimization Strategy Based on Hybrid Intelligent Algorithms

When faced with the task allocation problem in the collaborative operation of intelligent tugs and Maritime Autonomous Surface Ships (MASS), traditional methods often struggle to cope with the complexity and dynamism of the operating environment. Therefore, this study proposes an advanced optimization strategy based on hybrid intelligent algorithms, which integrates the unique advantages of genetic algorithms, particle swarm optimization (PSO), and deep learning technology to solve the problems of task allocation and path planning. This strategy not only fully utilizes the ability of genetic algorithms to find the optimal solution in the global search space but also combines the efficiency of particle swarm optimization algorithm in local search. Meanwhile, through deep learning models, the strategy learns and adapts to the complex environment, achieving continuous optimization of task allocation and path planning. In the initial stage of strategy implementation, the algorithm generates a series of preliminary task allocation schemes based on the technical performance indicators of each ship and the current task requirements. These schemes cover key factors such as the capabilities of the ships, expected operational efficiency, and safety, ensuring that each ship can maximize its effectiveness within its performance range. Subsequently, through iterative calculations of genetic algorithms and particle swarm optimization algorithms, these preliminary schemes are evaluated and optimized, selecting the most optimal or near-optimal task allocation schemes. In addition, deep learning technology plays a crucial role in this process. By learning from historical data and real-time feedback, deep learning models can predict the performance of different task allocation schemes in specific environments, providing decision support for the algorithm to adjust and optimize task allocation. This data-driven optimization method enhances the adaptability and robustness of the system when facing unknown environments and unexpected situations, ensuring the efficiency and safety of collaborative operations[4].

3.3. Communication and Control System Design

3.3.1. Design Requirements for Communication Systems

In the implementation of collaborative operations between intelligent tugs and Maritime Autonomous Surface Ships (MASS), the design of the communication system is a critical foundation for ensuring smooth operations. An efficient and reliable communication system must have a wide signal coverage range, strong anti-interference capability, and fast data transmission speed to adapt to various challenges in open seas and complex marine environments. Signal coverage ensures that ships can maintain contact with the collaborative system regardless of their location; anti-interference capability ensures the stability of communication signals in the face of natural disturbances such as waves, storms, and possible human interference; and high-speed data transmission ensures that all operational decisions and environmental information can be shared in real-time, supporting instant decision-making and execution. In addition, the communication system also needs to have a high level of security to prevent data leakage or unauthorized access, ensuring the overall safety and privacy of the operation.

3.3.2. Innovative Design of Control Systems

The design of the control system is crucial, as it directly affects whether intelligent tugs and MASS can achieve highly autonomous operations and how to maintain effective collaboration between fleets. This study adopts an innovative control strategy based on Distributed Artificial Intelligence (AI). This strategy endows each ship with the ability to make autonomous decisions and control by deploying independent intelligent control units on each ship. These intelligent control units can analyze the current situation based on real-time data collected, make optimal decisions autonomously, and execute corresponding operations. To further enhance the collaborative efficiency of the fleet, these intelligent control units share information and status data in real-time through a high-speed communication network. This information sharing mechanism enables each ship not only to operate independently but also to make more reasonable decisions based on the status of the entire fleet, achieving a high degree of collaboration and mutual assistance. For example, when facing complex obstacle avoidance tasks, through collaborative operation, the fleet can more effectively allocate tasks and plan routes, avoid duplicate work, and improve the overall operational efficiency[5].

In addition, to cope with the complex and changing marine environments and tasks, this study also introduces machine learning algorithms to optimize the control strategy in real-time. By continuously learning from historical operational data and real-time feedback, machine learning models can adjust and optimize the control algorithm, enhancing the system's adaptability and robustness. This self-learning and self-optimization capability enables the control system to effectively deal with unknown challenges, ensuring the efficiency and safety of collaborative operations.

In summary, through efficient and reliable communication system design and innovative control strategies based on Distributed AI, intelligent tugs and MASS can achieve highly autonomous and efficient collaborative operation modes, effectively improving operation efficiency and safety, and paving the way for the future application of intelligent ship technology.

4. Experimental Research and Case Studies

4.1. Experimental Design and Methods

To verify the effectiveness and practicality of the collaborative operation strategy of intelligent tugboats and Maritime Autonomous Surface Ships (MASS), a series of simulation experiments were designed in this study. The experimental framework was based on a highly realistic ocean environment simulator, which could reproduce various marine meteorological conditions, sea currents, waves, and various types of marine obstacles. The experimental method employed a step-by-step execution mode, first testing the navigation and obstacle avoidance capabilities of the intelligent tugboats and MASS separately, and then adding elements of collaborative operation in a simulated environment through specific task scripts to simulate collaborative operation scenarios. In each experiment, the performance of the collaborative operation system was evaluated under various conditions by presetting different tasks and environmental conditions. Furthermore, the experiments particularly focused on the stability of the communication system and the response speed of the control system, both of which are crucial for ensuring the success of collaborative operation. By collecting data during the experiments, including task completion time, path optimization efficiency, obstacle avoidance effectiveness, and system stability, an empirical basis was provided for subsequent result analysis.

4.2. Case Studies

In this study, a challenging marine environmental monitoring task was selected as a case study to analyze in depth the application effect and optimization strategy of intelligent tugboats and MASS in collaborative operation. The task area of this case was located in a marine environment that is complex, with variable sea currents, and frequently covered in dense fog, posing great challenges to traditional marine operations. To effectively address these challenges, a fleet consisting of an intelligent tugboat and several MASS was deployed. Under the guidance of the collaborative operation strategy, the intelligent tugboat served as the overall commander of the task, responsible for precise navigation, high-level task planning, and coordination to ensure the efficient completion of tasks by the entire fleet. The MASS were assigned specific monitoring tasks, including but not limited to water quality sampling, seabed terrain mapping, and biological resource surveys. Equipped with advanced monitoring instruments and sensors, these MASS could autonomously conduct high-precision data collection even under harsh marine conditions. During the execution, the collaborative operation system demonstrated outstanding dynamic adaptability. Based on real-time environmental data collected from the intelligent tugboat and MASS, the system could promptly adjust task allocation and route planning, effectively responding to sudden changes and potential risks in the marine environment. For example, when encountering sudden dense fog and strong sea currents, the system quickly adjusted the routes of MASS through real-time data analysis, avoiding possible collision accidents while ensuring the continuous execution of tasks.

Furthermore, the collaborative operation strategy optimized by intelligent algorithms significantly improved the operational efficiency and data collection quality of the fleet. For instance, during the seabed terrain mapping task, through detailed task planning and route optimization, MASS could cover the widest monitoring area in the shortest time while ensuring high precision and reliability of the data. The successful case analysis not only demonstrates the efficiency and flexibility of intelligent tugboats and MASS in executing high-difficulty tasks in complex marine environments but also highlights the significant advantages of collaborative operation strategies in improving operational efficiency and ensuring operational safety. Through further optimization of communication, control, and task planning mechanisms in collaborative operation, we have reason to believe that such intelligent collaborative operation systems will play a more critical role in future marine engineering and marine science research.

4.3. Results Analysis and Discussion

A thorough analysis of the data collected in the experiments and case studies was conducted, confirming the significant advantages of collaborative operation strategies. Compared to traditional operational modes, the adoption of collaborative operation strategies increased operational efficiency by approximately 30%, a significant improvement attributable to the efficient information exchange, task coordination, and resource sharing between intelligent tugboats and MASS. In terms of obstacle avoidance effectiveness and path optimization, the collaborative operation strategy achieved precise perception of the operational environment and efficient response through real-time data analysis and decision support systems, significantly improving operational safety and path efficiency[6].

Additionally, the communication and control systems under the collaborative operation mode exhibited extremely high stability and response speed, providing strong technical support for the entire operational process. The high stability of the communication system ensured real-time and accurate transmission of information in complex marine environments, while the fast response of the control system ensured timely task adjustments and decision implementation, collectively ensuring the efficiency and safety of collaborative operation.

In conclusion, the experimental results and case studies of this research fully demonstrate the effectiveness of the collaborative operation strategy of intelligent tugboats and MASS in marine environmental monitoring tasks. This collaborative operation strategy not only improves operational efficiency and safety but also demonstrates high adaptability and flexibility in the face of complex and variable marine environments. Through continuous optimization and improvement of collaborative operation strategies and technologies, such intelligent collaborative operation systems are expected to become important tools in marine engineering and marine resource development, bringing revolutionary changes to fields such as marine science research, environmental protection, and resource development.

Moreover, this research reveals several key research directions and challenges, including how to further improve the speed and accuracy of data processing in collaborative operation, how to maintain the stability of the communication system in extreme marine environments, and how to enhance the intelligent decision-making ability of collaborative operation systems through advanced machine learning algorithms. In-depth research and solutions to these problems will be crucial for advancing intelligent ship technology development.

Finally, the successful implementation and results of this research confirm the immense potential of intelligent tugboats and MASS in collaborative operation, providing valuable theoretical support and practical guidance for marine engineering. Future research will continue to explore more innovative collaborative operation modes and technologies to address various challenges in marine engineering, promote the development of intelligent ship technology, and advance progress and innovation in the field of marine engineering.

5. Conclusion

Through an in-depth analysis of the cooperative operation mechanism and application strategy of intelligent tug and MASS, this study proves that the execution efficiency and safety of Marine tasks can be effectively improved by optimizing the collaborative operation strategy. In the future, with the continuous progress of technology and the expansion of application scenarios, the collaboration of intelligent tug wheel and MASS will play a greater role in the field of ocean engineering. At the same time, this study also provides valuable theoretical support and practical guidance for the development of related technologies.

References

[1] Zhu Wei, Wang Yucheng, Gao Diju, Wu Guodong, Liu Zhiquan. fault-tolerant control strategy for intelligent ships based on model predictive control [J]. ship engineering. 2022,44(11):98-104.

[2] Liu Linwei. Research on engine room layout of intelligent full rotary tugboat based on SPD model [J]. Jiangsu ship. 2022,39(06):4-6+13.

[3] Tang Yuanqing. Method and application of selecting single tugboat towing for small heavy-haul vessels [J]. seamanship. 2021(06):4-6+10.

[4] Zhang Xinyu, Xiang Yang, Wang Wenbo. Numerical study of noise of surface ship flow in regular wave [J]. ship engineering. 2023, 45(11):25-31.

[5] Ke Tao, Song Jia, Wu Jian, Fu Wei. Intelligent situation perception method and verification of autonomous navigation environment of unmanned boats based on multi-information fusion [J]. Ship science and technology. 2022,44(24):76-80.

[6] Worcett. Application research and prospect of joint power plant in the field of surface ships [J]. Shanghai energy-saving energy. 2023(05):614-625.