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Research Idea of Underwater Autonomous Operating Robot Based on Marine Industry of Shandong Province

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Abstract: Since the 21st century, humanity has continually increased its efforts in ocean exploration and resource development, making the ocean an important venue for countries around the world to compete for maritime rights, develop high-tech technologies, engage in international cooperation, and showcase their strength. However, as human exploration and development activities in the ocean have deepened, the mission requirements have become increasingly complex and diversified. There is a need for high-standard construction of marine science and technology achievement transfer and transformation centers, improvement of the achievement transfer and transformation system, and promotion of deep integration of the industrial chain, innovation chain, and capital chain. This fosters the landing and transformation of more marine science and technology achievements, forming marine science and technology industrial clusters with distinctive characteristics, differential development, and strong competitiveness in coastal cities, and cultivating a perfect modern marine industry system. This has led to increased attention and in-depth research by numerous scholars on the collaborative operation and control of underwater intelligent agents, gradually becoming a mainstream trend and development direction in the field of underwater robots in recent years. "China's Discipline Strategic Planning-Control Discipline" lists the autonomous control of collaborative operations of multiple underwater robots as one of the mid-to-long term development trends and forefront scientific issues in the research of 'underwater vehicles'. This project will fully consider the complex ocean current environment, adhere to the world's scientific and technological frontiers, and carry out advanced interdisciplinary and cross-field basic and applied research around fields such as synthetic biology and artificial intelligence, promoting the integration and penetration of science, technology, engineering, industry, and market.

1. Introduction

Shandong Province is a major maritime province with abundant marine resources, a strong foundation in marine industries, and advanced marine science and technology, which has significantly enhanced its comprehensive strength in the marine economy. For instance, in 2023, Shandong's marine bio-pharmaceutical industry took the lead, gathering more than 80% of China's

marine drug research resources and capabilities. The industry's added value exceeded 20 billion yuan, ranking first nationwide. It centers on the development of modern marine industries, integrates and opens up the maritime and terrestrial economies, and employs modern high-tech and management methods. This approach fosters the interconnected development of various related economies, thereby creating an economic form with strong international competitiveness.

Since the 21st century, there has been a gradual increase in the exploration and development of marine resources, with underwater autonomous operation robots, as the protagonists of marine exploration, receiving significant attention. This area of research has become a forefront field in robotics innovation. Underwater robots, relying on their own propulsion, can carry out actions autonomously for extended periods, and are characterized by intelligence, mobility, and stealth. As the exploration and development of the ocean deepens, the variety of demands becomes increasingly complex and diversified. Simple optimization of traditional single underwater robots against one type of metric is no longer sufficient to meet these needs. Therefore, research on the collaborative operation and control of multiple underwater robots has attracted high attention from scholars. "China's Discipline Strategic Planning-Control Discipline" [1] lists the collaborative operation and control of multiple underwater robots as one of the mid-to-long term development trends and forefront scientific issues in the study of 'underwater vehicles'.

The foundation of autonomous movement and coordination of underwater robots is a good perception of the surrounding aquatic environment. Underwater robots can perceive their environment through optical, pressure, and sonar sensors. Literature [2]-[6] has utilized artificial lighting compensation, image enhancement algorithms, and other technical means to overcome many physical factors that cause image blur. Additionally, robots equipped with sonar and pressure sensors [7]-[9] can achieve perception and mapping of complex aquatic environments. Depending on the roles of multiple underwater robots in the collaborative control scheme, they can be divided into leader-follower and parallel modes. In the leader-follower mode, the robot acting as the leader needs to be equipped with high-precision navigation devices to serve as a reference point for other robots. Followers refer to the leader's position information and make adjustments according to the system's requirements, which is a mature positioning configuration currently in use [10]-[15]. In the parallel mode, all robots are equal without a hierarchical distinction, making this configuration more flexible, and some robots can be equipped with high-precision navigational instruments as needed [16]. However, underwater robots still face the following difficulties in underwater environment mapping: (1) Current environmental perception methods lack the ability to restore scenes accurately. When there are obstructive factors in the aquatic environment, intensive sampling is required, leading to repetitive work scenarios; (2) While existing technologies can describe static environments well, modeling dynamic environments poses a challenge, impacting the adaptability and usability of underwater robots.

This project, taking into account the complexity of the underwater environment and the incompleteness of underwater information exchange, decomposes the key technologies of the underwater robot collaborative and control system. It delves into the structural design (hardware) and autonomous control (software) theories and technologies of the multi-underwater robot system. By overcoming the adverse effects of random factors in complex environments, this underwater robot operation system holds significant theoretical and practical value in the exploration and development of marine resources in Shandong Province.

2. Research Ideas and Objectives

This project focuses on the collaborative and control system of underwater operation robots, studying several key technologies and basic theories of distributed collaborative control of

underwater operation robots. This includes the distributed collaborative positioning and control of underwater operation robots based on dynamic networking technology and other key foundational theories. The project expects to achieve the following objectives:

(1) The project will analyze the impact of random factors on information transmission in complex marine environments and design positioning algorithms. Monitoring the marine environment requires the system to objectively analyze and precisely locate the environment, which is the basis for the collaborative operation of multiple underwater robots. This project fully considers the impact of random factors on the system to avoid the influence of complex underwater environments on collaborative control, studies positioning under incomplete information conditions, and provides positioning algorithms.

(2) It will design a multi-underwater robot collaborative control algorithm that meets environmental requirements. The design of the algorithm aims to improve the efficiency of operations and the robustness and reliability of the entire system's collaborative work. The challenges faced at this stage mainly include establishing the dynamic model of robots and overcoming the impact of random factors in communication channels. Therefore, during the project's progression, it can flexibly leverage other algorithms, such as leader-follower control, asymmetric information control, etc., all of which can provide a theoretical basis for the implementation of this project.

3. Key Scientific Problems

Regarding the research content mentioned above, this project aims to address the following key issues:

(1) Filter design under incomplete information conditions

Since the system involves autonomous operation of robots, researchers cannot directly receive information emitted by the robots. Here, an observer is used to observe signals and carry out the process for the controller algorithm, which becomes the design of the filter. This is a critical step in the collaborative and control system of multiple underwater operation robots. The implementation of this algorithm provides strong theoretical support for subsequent underwater environment monitoring, target tracking, etc. Due to the incompleteness of the information, the information observed for each robot and the filters involved in the controller differ, so designing high-precision, strong robustness, and high timeliness filters is a key scientific problem that needs to be solved.

(2) Collaborative control under incomplete information conditions

Collaborative control determines whether multiple underwater robots can perform formation control, target tracking, etc., according to pre-set requirements. Based on previous research achievements, existing algorithms are optimized and iteratively updated to make the collaborative algorithm adapt to more complex marine environments. When designing the algorithm, it is necessary to consider the communication protocols between the robots, the randomness and uncertainty of the environment, the diving depth, and the impact of signal delay on the controller, among others. This represents another critical scientific issue that this project faces.

4. Research Methods and Technical Routes

4.1. Implementation of Positioning for Multiple Underwater Autonomous Operating Robots

Filter design under incomplete information conditions. In the complex underwater environment, the transmission of information is subject to delays and randomness, and it is time-varying, with packet loss during the information transmission process having certain probabilistic characteristics. Therefore, when describing the kinematic model, it is necessary to consider the impact of

multiplicative noise and the reliability of the transmission channel for signal transmission. In control theory research, the filter design for time-delay systems with time-correlated multiplicative noise remains an unresolved theoretical challenge.

Filter design for packet loss in information transmission under random delays. Introducing the Z-X-L function to handle random delay situations and designing packet loss filters, the theory of innovation recombination and other reconstruction theories can handle delay items in the modeling system. The design of such algorithms transforms random delay observation control systems into systems without delays; constructing reasonable index functions and employing techniques such as the matrix maximum principle, Lyapunov function construction method, complete matching method, geometric projection, etc., for the design of optimal or suboptimal filters; utilizing online algorithms of reinforcement learning to estimate real-time information and design control laws, thereby establishing high-precision evaluation index functions. By analyzing the threshold of the error index function, the control laws are ensured to meet the system's convergence and stability conditions.

4.2. Collaborative Control of Multiple Underwater Autonomous Operating Robot Systems

Consistency control design for random systems. Due to the complexity of underwater robots' structure and functions, random uncertain factors occur in the modeling process, which appear in the system equations in the form of multiplicative noise. Starting from the optimal control problem, this project proposes a control strategy design method for systems with multiplicative noise. This approach utilizes Lyapunov functions to establish necessary and sufficient conditions for consistency.

Consistency control design for packet loss in information transmission under random delays. Packet loss in information transmission under random delays is another problem to be addressed in this project. Assuming that the system's delay items are constant, based on the design idea of consistency control for multiplicative noise systems, the feedback gain of the closed-loop system and the sufficient and necessary conditions for system stability are obtained, and the maximum delay boundary is determined based on the obtained system parameters and feedback gain; by using an observer to obtain the system information under the current state, and combining available historical information to design a state feedback protocol, a consistency control strategy for the problem of packet loss in information transmission under random delays is provided.

5. Standardization and Industrialization of Autonomous Underwater Operation Robots

As an important maritime province in China, Shandong Province boasts rich marine resources and an advanced marine technology base. With technological progress, the application of autonomous underwater operation robots in the marine industry has become increasingly widespread, becoming a key technology in fields such as marine exploration, resource development, and environmental protection. Therefore, an in-depth discussion on the standardization and industrialization of this field is of great significance for the development of the marine industry in Shandong Province and globally.

5.1. Standardization Driving Technological Development and Industry Upgrading

Shandong Province needs to establish a complete set of standard systems for autonomous underwater operation robots, including design, manufacturing, testing, and operational standards, to ensure the performance, safety, and reliability of the robots. Standardization not only helps to promote technological development and innovation but also facilitates compatibility and interoperability between different equipment and systems, improving overall operational efficiency.

5.2. Industrialization Promoting Regional Economic Growth

The industrialization of autonomous underwater operation robots is a new driving force for the development of Shandong's marine economy. By encouraging corporate investment in research and development, a number of core competitive underwater robot enterprises can be formed, promoting the perfection and extension of the industrial chain. Shandong Province can leverage its marine resources and geographical advantages to develop application areas such as deep-sea exploration, submarine pipeline maintenance, and marine environment monitoring, creating demonstration areas for the application of autonomous underwater operation robots.

5.3. International Cooperation and Exchange

In the process of standardization and industrialization, Shandong Province should strengthen cooperation and exchange with the international marine science and technology community. By introducing and sharing international standards, the international competitiveness of local enterprises can be enhanced. Shandong's technology companies actively participate in international projects and exhibitions to promote the region's autonomous underwater operation robot technology and products, thereby expanding their presence in the international market.

5.4. Policy Support and Talent Cultivation

The Shandong Provincial Government should formulate policies to support the development of the autonomous underwater operation robot industry, including financial support, tax incentives, market access, etc., to provide a favorable policy environment for industrialization. The government and industry leaders are working to strengthen talent cultivation and introduction. They cooperate with universities and research institutions to cultivate a group of composite talents who understand technology, management, and the market, thereby providing human resource support for industrial development. In summary, through the dual promotion of standardization and industrialization, Shandong Province can achieve technological innovation and industrial upgrading in the field of autonomous underwater operation robots, contributing to the sustainable development of the marine economy.

6. Conclusions

In the 21st century, with the continuous intensification of human activities in ocean exploration and resource development, the ocean has become an important platform for international cooperation, high-tech development, maritime rights competition, and the demonstration of national strength. This trend has prompted the rapid development of marine science and technology, especially the advancement of underwater robot technology, which has become key to pushing the new stage of ocean exploration and resource utilization.

To address these challenges, interdisciplinary research has become necessary, focusing on cutting-edge technological fields such as synthetic biology and artificial intelligence, and promoting deep integration of science, technology, and industry. "China's Discipline Strategic Planning-Control Discipline" identifies the autonomous control technology of collaborative operations of multiple underwater robots as a mid-to-long term development trend and a forefront scientific issue, highlighting its importance in future marine science and technology development. Moreover, to promote the transfer and transformation of scientific and technological achievements, establishing high-standard marine science and technology achievement transformation centers, improving the achievement transfer and transformation system, and promoting deep integration of the industrial

chain, innovation chain, and capital chain are crucial for nurturing competitive marine science and technology industrial clusters and building a perfect modern marine industry system. By in-depth research into the collaborative control and operation technology of underwater robots, this project aims to drive marine technological innovation, accelerate the exploration and development of marine resources, and contribute to the sustainable development of the marine economy.

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