氏　　名（本籍）	李　春英（中国）
専　　攻	知能機械システム工学専攻
学位の種類	博士（工学）
学位記番号	博甲第180号
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論文審査委員	（主査）鈴木　桂輔 （副査）前山　祥一 （副査）石原　秀則

論文内容の要旨

Spherical Underwater Robot (SUR) is a kind of special structural underwater robot with low-noise and high compression characteristics. Due to its overall symmetry, there are no coupling terms in the fluid dynamics calculation. Therefore, it is widely used in underwater missions. There are many researchers in the world who are committed to developing spherical robots. In the previous research in our laboratory, the open water efficiency, mutual interference and availability for SUR with hybrid thrusters are not efficient enough. Moreover, the attitude regulation and multi-mode switching strategies considering the robot model, uncertainties, and anti-disturbance for SURs are inadequate. More importantly, the rich multi-source information from different types of sensor nodes for SURs has not yet formed a relatively specific theory and method. To address these issues, the multi-sensor information fusion and control strategy for the SUR with hybrid thrusters is proposed.

The thesis consists of 8 chapters as follows:

Chapter 1: Introduction

In this chapter, the need for maneuverability, stability and effectiveness of the SUR is introduced in order to perform tasks safely and efficiently.

Chapter 2: Mechanical design and modeling of the SUR

The novel SUR with hybrid propulsion devices is proposed, including the hybrid thruster unit, the sensor unit, the decision unit and the power unit. Considering the strong nonlinearities, external disturbances and obstacles, the kinematic and dynamic model of the SUR is described.

Chapter 3: Hydrodynamic and open-water performance of the SUR with hybrid propulsion

devices (Journal #1)

To improve the accuracy and efficiency of the SUR, the hydrodynamic characteristics of hybrid propulsion devices are analyzed. The open-water performance and flow field of individual water-jet and propeller thrusters are analyzed using ANSYS WORKBENCH. The thrust measurement and basic motion experiments for SUR using hybrid propulsion devices are carried out.

Chapter 4: Development of the multi-mode switching control of the SUR (Journal #2)

A multi-mode adaptive switching strategy for the SUR combining the advantages of each thruster is proposed, which provides the possibility for the SUR to choose the optimal control mode according to the unpredictable operating environment. A series of multi-mode switching experiments are conducted using the water-jet mode, propeller mode and hybrid mode. By adding external disturbances and other comparative experiments, the effectiveness and accuracy are further verified.

Chapter 5: Performance evaluation of an attitude controller of the SUR (Journal #3)

A suitable self-balancing mechanism and an attitude controller for the SUR are proposed. The center of gravity adjustment structure is designed. The attitude controller for the SUR is developed by dividing the attitude control problem into roll angle control and pitch angle control. Two nonlinear disturbance observers are constructed to handle errors in the uncertainties and linearization process in the dynamic model. The back-stepping sliding mode control method is implemented for SUR to improve the robustness and feasibility of the attitude controller. A series of experiments are conducted to verify the performance of the developed method.

Chapter 6: Improved obstacle avoidance strategy based on the ultrasonic sensor array (Journal #4, #5)

In this chapter, the waypoints-based trajectory tracking with obstacles and uncertainties is proposed to ensure its safety and stability. An obstacle avoidance control strategy for the SUR is developed based on the ultrasonic sensor array. The stability and robustness of the control system are verified using the Lyapunov theory. A series of simulations and experiments in the real environment is conducted to evaluate the performance of the control strategy for detecting unknown environments.

Chapter 7: Performance evaluation of the multi-sensor information fusion of the SUR (Journal #6)

Multi-source information fusion is an important guarantee for improving the quality of data analysis and processing. Considering the key issues such as attitude estimation, positioning and obstacle avoidance involved in performing tasks, a fusion model for SUR is proposed by constructing the optimized prediction models. The

correlation and fusion scheme between multiple sensors is developed. A series of locomotion and obstacle avoidance experiments are performed by integrating the fusion model into the SUR to comprehensively evaluate the performance metrics.

Chapter 8: Conclusion

To expand the comprehensive capability of SUR to the underwater environment and realize long-term monitoring and exploration tasks, this thesis focuses on using multi-sensor technology to improve the perception and obstacle avoidance capabilities of SUR in complex environments. The summary of the conclusion is as follows:

1) The SUR with hybrid thruster is designed and the open-water performance of the hybrid thruster is evaluated using a numerical calculation to improve the execution efficiency, multimodality and maneuverability.

2) Control strategies for the SUR, including attitude regulation and multi-mode adaptive switching, are proposed based on the kinematic and dynamic models.

3) The multi-sensor information fusion model for SURs is proposed by constructing the optimized prediction models, such as the attitude estimation model, velocity estimation model, obstacle avoidance model, and so on.

審査結果の要旨

Spherical Underwater Robot (SUR) is a kind of special structural underwater robot that has characteristics of low-noise and high compression. Due to its overall symmetry, there are no coupling terms in the fluid dynamics calculation. Therefore, it is widely used in underwater missions. There are many researchers in the world who are committed to developing spherical robots. In the previous research in our laboratory, the open water efficiency, mutual interference and availability for SUR with hybrid thrusters are not efficient enough. Moreover, the attitude regulation and multi-mode switching strategies considering the robot model, uncertainties, and anti-disturbance for SURs are inadequate. More importantly, the rich multi-source information from different types of sensor nodes for SURs has not yet formed a relatively specific theory and method. To address these issues, the multi-sensor information fusion and control strategy for the SUR with hybrid thrusters is proposed.

The contents of this doctoral thesis are as follows:

Chapter 1: Introduction

This chapter describes the importance of the introduction of the SUR. The need for maneuverability, stability and effectiveness of the SUR is introduced in order to perform tasks safely and efficiently.

Chapter 2: Mechanical design and modeling of the SUR

The novel SUR with hybrid propulsion devices is proposed, including the hybrid thruster unit, the sensor unit, the decision unit and the power unit. Considering the strong nonlinearities, external disturbances and obstacles, the kinematic and dynamic model of the SUR is described.

Chapter 3: Hydrodynamic and open-water performance of the SUR with hybrid propulsion devices (Journal #1)

To improve the accuracy and efficiency of the SUR, the hydrodynamic characteristics of hybrid propulsion devices are analyzed. The open-water performance and flow field of individual water-jet and propeller thrusters are analyzed using ANSYS WORKBENCH. The thrust measurement experiments and the basic motion experiments for SUR using hybrid propulsion devices are carried out.

Chapter 4: Development of the multi-mode switching control of the SUR (Journal #2)

A multi-mode adaptive switching strategy for the SUR combining the advantages of each thruster is proposed, which provides the possibility for the SUR to choose the optimal control mode according to the unpredictable operating environment. A series of multi-mode switching experiments are conducted using the water-jet mode, propeller mode and hybrid mode. By adding external disturbances and other comparative experiments, the effectiveness and accuracy are further verified.

Chapter 5: Performance evaluation of an attitude controller of the SUR (Journal #3)

A suitable self-balancing mechanism and an attitude controller for the SUR are proposed. The center of gravity adjustment structure is designed. The attitude controller for the SUR is developed by dividing the attitude control problem into roll angle control and pitch angle control. Two nonlinear disturbance observers are constructed to handle errors in the uncertainties and linearization process in the dynamic model. The back-stepping sliding mode control method is implemented for SUR to improve the robustness and feasibility of the attitude controller. A series of experiments are conducted to verify the performance of the developed method.

Chapter 6: Improved obstacle avoidance strategy based on the ultrasonic sensor array (Journal #4, #5)

In this chapter, the waypoints-based trajectory tracking with obstacles and uncertainties is proposed to ensure its safety and stability. An obstacle avoidance control strategy for the SUR is developed based on the ultrasonic sensor array. The stability and robustness of the control system are verified using the Lyapunov theory. A series of simulations and experiments in the real environment is conducted to

evaluate the performance of the control strategy for detecting unknown environments.

Chapter 7: Performance evaluation of the multi-sensor information fusion of the SUR (Journal #6)

Multi-source information fusion is an important guarantee for improving the quality of data analysis and processing. Considering the key issues such as attitude estimation, positioning and obstacle avoidance involved in performing tasks, a fusion model for SUR is proposed. By constructing the optimized prediction models, the correlation and fusion scheme between multiple sensors is developed. A series of locomotion experiments and obstacle avoidance experiments are performed by integrating the fusion model into the SUR to comprehensively evaluate the performance metrics.

Chapter 8: Conclusion

To expand the comprehensive capability of SUR to the underwater environment and realize long-term monitoring and exploration tasks, this thesis focuses on using multi-sensor technology to improve the perception and obstacle avoidance capabilities of SUR in complex environments. The summary of the conclusion is as follows:

1) The SUR with hybrid thruster is designed and the open-water performance of the hybrid thruster is evaluated using a numerical calculation to improve the execution efficiency, multimodality and maneuverability.

2) Control strategies for the SUR, including attitude regulation and multi-mode adaptive switching, are proposed based on the kinematic and dynamic models.

The multi-sensor information fusion model for SURs is proposed, by constructing the optimized prediction models, such as the attitude optimization model, velocity estimation model, depth estimation model, and obstacle avoidance model.

最終試験結果の要旨

令和5年7月14日に公聴会ならびに最終試験を実施した。公聴会では審査申請者に学位論文の内容に関する発表を課した（40分間）。その後、口述試験として学位論文の内容に関わる審査委員の質疑に対して的確に答えることを求め、学位論文に関連した分野の専門知識を確認した（30分間）。以上の結果、審査員の質疑に対して適切に回答がなされた。主たる質疑に対する回答を以下に示す。

１）今回の実験では、プールにおいて、姿勢制御器の動作検証や障害物の回避実験を行っている。実際の動作環境として想定される海中では、同様な性能を発揮できると言えるか？特に、ステッピングモータを用いてバランサーの位置を制御し、姿勢制御するシステムの応答性は十分なのか？

【回答】今回の実験では、プールでの実験ではあるが、ある程度の外乱を与えた実験を実

施している。外乱が発生する環境下での姿勢制御実験において、周波数応答の観点での評価は実施していないが、結果として姿勢を維持する機能は十分に備えていることを確認している。また、姿勢センサへの外乱入力については、カルマンフィルタを用いて姿勢推定の精度を向上させており、要求条件を満足する姿勢制御性能を実現している。

２）海洋分野での水中ロボットの作業では、単一のロボットのみでなく、他のロボットと連携した作業が必要と思われる。どのような課題が考えられるか？
【回答】ご指摘のように、母船とロボットとの通信のみでなく、個々のロボット間での通信も重要となる。海中では、画像センサなどが十分な性能を発揮できないと思われるため、ソナーを用いたロボット間での通信技術の確立が重要と考えており、今後の課題である。

３）水中ロボットについては、諸外国で類似の研究が実施されていると思う。この研究の最もオリジナリティの高い内容は何か？
【回答】独自に設計開発した、推進用ハイブリッドスラスター、姿勢の制御方法、超音波センサーアレイを用いた障害物の検知方法である。これらの技術により、類似の研究事例と比較して、推進性能、姿勢制御、障害物の回避性能は高い。

本審査委員会における審査は、学位論文の内容、研究方法について審査および確認するものである。博士の学位論文を作成するにあたり、主論文として６件の査読つき学術論文がある。本審査委員会は、提出された博士学位請求論文が博士（工学）の学位に値するものであり、審査申請者は専門領域に関する十分な学識と研究能力を有するものと判断した。以上より、本最終試験の評価を合格とする。