International Scientific Technical and Economic Research | ISSN: 2959-1309 | Vol.3, No.3, 2025
www.istaer.online——Research Article

Human Failure Analysis and Fault-Tolerant Interaction Design of Deep-Sea Exploration Robots

Jialin Sun

Shandong University of Science and Technology, Shandong, China

Received: 23 Jul 2025
Revised: 31 Jul 2025
Accepted: 05 Aug 2025
Published: 16 Aug 2025
Copyright: © 2025 by the authors. Licensee ISTAER. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/license s/by/4.0/).

Abstract: Human-induced failures in deep-sea exploration robots are a key factor affecting the safety and reliability of deep-sea operations. This study systematically analyzes the mechanisms and influencing factors of human-induced failures in the extreme deep-sea environment and proposes a multi-layered fault-tolerant interaction design approach. By constructing a three-dimensional human-induced failure classification model, the authors reveal the coupled relationship between environmental pressure, task complexity, and operator cognitive characteristics. The developed layered fault-tolerant architecture provides comprehensive protection, from hardware redundancy to cognitive collaboration. Experimental results show that it can reduce the incidence of typical human-induced failures by 65%-78%. The study innovatively proposes the concept of "predictive fault tolerance," combining digital twins with operational model learning to enable the system to anticipate risks. Dynamic interface optimization and multimodal feedback strategies significantly enhance the operator's situational awareness. The research findings provide a systematic theoretical framework and practical guidance for the design of deep-sea exploration robots, promoting a paradigm shift from a "machine-centric" approach to a "human-machine collaborative" approach, and are of significant significance for improving the safety and efficiency of deep-sea operations.

Keywords: Deep-sea exploration robots; Human error; Fault-tolerant design; Human-computer interaction; Digital twin; Multimodal feedback

1 INTRODUCTION

Deep-sea exploration robots are the core tools for human exploration of marine resources and research of deep-sea environments. Their technological development is directly related to the breakthrough of national marine strategy and scientific research. With the increasing complexity of deep-sea exploration missions, the environmental pressure, operational difficulty and uncertainty faced by robot systems have increased significantly, and failures caused by human factors have become one of the key issues that restrict the success of missions [1]. From operator misjudgment to interface design defects, human failures may not only cause equipment damage or data loss but may even trigger chain safety accidents. In this context, studying the human failure mechanism of deep-sea exploration robots and designing efficient fault-tolerant interaction systems can not only improve mission reliability, but also provide theoretical support for the development of autonomous equipment in extreme environments, which has important engineering value and scientific significance [2].

Currently, deep-sea exploration robots have evolved from early remote-control operations to intelligent and autonomous ones, but technical bottlenecks are still prominent. On the one hand, extreme conditions such as high pressure, low temperature and low visibility in the deep sea pose severe challenges to the perception and decision-making capabilities of robots; on the other hand, the human-machine collaboration model still relies on the operator's experience and judgment. Problems such as remote-control delays and insufficient information display are very likely to induce human errors [3]. Such as in the actual operation of the Jiaolong manned submersible, the robot arm operated abnormally due to the untimely feedback of the interface alarm. Similar cases show that it is difficult to completely avoid human risks by relying solely on hardware redundancy or algorithm optimization. It is urgent to reconstruct the fault tolerance of the system from the perspective of human-machine collaboration.

The core of human failure analysis and fault-tolerant interaction design lies in incorporating "human limitations" into technical solutions. Traditional fault analysis focuses on mechanical or electrical problems of the equipment itself, while ignoring subjective factors such as the operator's cognitive load and lack of situational awareness. In fact, more than 40% of abnormal events in deep-sea exploration missions are directly related to human operations. Through fault-tolerant interaction design - such as adaptive interface, misoperation suppression mechanism and intelligent alarm system - the probability of human error can be effectively reduced, and when a fault occurs, the operator can be guided to make quick corrections through multimodal feedback [4]. This research direction integrates human factors engineering, cognitive psychology and robotics technology, and is an important breakthrough in improving the robustness of deep-sea equipment.

This study aims to establish a human failure analysis framework for deep-sea exploration robots and propose a hierarchical fault-tolerant interaction design method based on it. By analyzing the mechanisms that trigger typical human-induced failures and integrating them with the specific characteristics of deep-sea missions, a fault-tolerant system is being constructed at three levels: hardware redundancy, software algorithms, and the human-machine interface. The goal is to establish design guidelines that can be applied to real-world projects through experimental verification, providing new insights into improving the reliability of human-machine collaboration in deep-sea robotics. The research will encompass fault mode discovery, fault-tolerant model construction, prototype system development, and simulation testing, forming a complete closed loop from theory to practice.

2 HUMAN FAILURE ANALYSIS OF DEEP-SEA EXPLORATION ROBOTS

Human-induced failures of deep-sea exploration robots refer to system anomalies or functional failures caused by cognitive limitations, operational errors, or misjudgments of operators, designers, or maintenance personnel in complex deep-sea operating environments. This type of failure is different from traditional mechanical or electronic failures. Its essence is the deviation caused by humans in the process of information processing, decision-making, or behavior execution. According to the manifestation and impact of the failure, it can be divided into direct operation failures (Such as accidentally touching the control button), cognitive judgment failures (Such as misreading sensor data), and system design failures (Such as operational confusion caused by unreasonable human-machine interface layout) [5]. What is more special is that the unpredictability of the deep-sea environment often amplifies the consequences of these human-induced errors. Such as under high pressure and low temperature conditions, a simple command delay may trigger a chain reaction, causing the robot arm to lose control or the thruster to fail.

In real deep-sea exploration missions, typical cases of human-induced failures often have distinct environmental specificity. In a deep-sea hydrothermal area exploration mission in 2019, the operator failed to notice the abnormal pressure of the robot arm hydraulic system in time due to information overload on the monitoring interface, which eventually led to the rupture of the mechanical joint seal. Another typical case occurred in 2021. Because the control software did not conduct a secondary confirmation of the operation instructions, the operator mistakenly pressed the "emergency ascent" button in a panic, resulting in the loss of precious geological samples carried by the robot [6]. These cases reveal the common characteristics of human-induced failures in deep-sea environments: they often occur in high-pressure and high-uncertainty mission stages; they are often closely related to interface design defects or unreasonable operation procedures; and the consequences are often irreversible. It is worth noting that deep-sea communication delays (Up to several seconds) will significantly aggravate such problems, making it difficult for ground control personnel to correct errors in time.

From the perspective of human-computer interaction, human errors in deep-sea exploration scenarios present a unique pattern. Operators are prone to decreased vigilance during long-term monitoring, resulting in missed inspections of key parameters; complex multi-task switching can easily lead to working memory overload, causing errors in the order of operation; and interface design without standardized feedback can lead to misjudgment of status. A typical example is that improper sonar data display methods cause operators to misjudge seabed protrusions as flat areas, causing scratches on the robot chassis. Even more insidious is the problem of "automation bias," where operators over-rely on the autonomous driving system and fail to take over control in a timely manner when the system experiences an anomaly. These error patterns differ significantly from those in conventional industrial environments, and their particularity stems mainly from the invisibility, limited communication, and high-risk nature of the deep-sea environment [7].

A deeper dive into the root causes of these human-induced failures reveals that they are complexly influenced by the environment, the task, and the operator. Extreme environmental factors such as high pressure, low temperature, and darkness not only affect equipment performance, but also indirectly affect operators—such as an uncomfortable environment in the control cabin can accelerate operator fatigue. In terms of mission characteristics, deep-sea exploration often requires simultaneous processing of multiple data streams from sonar, video, and sensors. This multi-tasking requirement can easily exceed human cognitive load. From the operator's perspective, insufficient professional knowledge, inappropriate stress response, and poor teamwork are all potential sources of risk [8]. It is particularly noteworthy that most current deep-sea robot systems fail to fully incorporate human factors engineering considerations during the design phase. The control interface layout, alarm prompt methods, etc. are often based on engineers' experience rather than the actual needs of operators. This "techno-centric" design philosophy itself is an important cause of human factors failures.

3 FAULT-TOLERANT INTERACTION DESIGN THEORY AND METHODS

The fault-tolerant interaction design of deep-sea exploration robots is based on the core principle of "prevention-tolerance-recovery". It aims to reduce the probability of human errors through systematic design methods and minimize their negative impact when errors are inevitable. Unlike traditional reliability design, fault-tolerant design pays special attention to the cognitive characteristics and behavioral patterns of human operators and uses multi-level protection mechanisms to make up for the weak links in human-machine collaboration. Its core goal is not to pursue absolute "zero errors", but to build an intelligent system that can adapt to

Sun., ISTAER. 2541 (2025)., 16 Aug 2025 https://doi.org/10.71451/ISTAER2541

human operation characteristics and has error buffering capabilities. In the special application scenario of deep-sea exploration, effective fault-tolerant design needs to meet three key indicators at the same time: the ability to identify operational errors early, the ability to adapt to abnormal conditions autonomously, and the ability to quickly mitigate the consequences of failures [9]. This design concept regards human limitations as input parameters of system design rather than external interference, reflecting the "human-centered" technology philosophy.

Constructing a human-machine fault-tolerant technology framework for deep-sea robots requires integrating theories and methods from multiple disciplines. At the hardware level, the use of redundant actuators and sensor cross-verification mechanisms can prevent system out-of-control caused by a single operation instruction; at the software level, intelligent monitoring algorithms based on behavioral pattern recognition can detect abnormal operation sequences in real time; and at the human-machine interface level, multi-channel feedback and progressive information presentation help maintain the operator's situational awareness [10]. It is particularly noteworthy that the fault-tolerant framework in the deep-sea environment must consider the special challenges brought by long-latency communication, which requires the system to have a higher degree of local autonomous decision-making capabilities. A typical solution is a layered fault-tolerant architecture: the bottom layer implements consistency verification of sensor data, the middle layer performs semantic analysis of operation intentions, and the top layer provides decision support and risk warnings. This architecture enables the system to identify and handle human errors at different granularities, avoiding the decline in efficiency caused by excessive intervention and effectively blocking the spread of error chains.

In view of the particularity of deep-sea exploration tasks, fault-tolerant interaction design needs to focus on solving several key requirements. The first is the need to simplify operations under stressful environments, reducing cognitive load through reasonable functional aggregation and contextualized interface presentation; the second is the need for autonomous fault tolerance under delayed communication conditions, and the system must have the ability to self-correct under limited supervision; the third is the need to guide attention during multi-tasking, and help operators focus on key information through multi-modal prompts such as vision, hearing, and even touch. Such as when a robot is simultaneously mapping terrain and collecting samples, the interface design should be able to dynamically adjust the information priority and automatically guide the operator's attention to the most urgent subtask [11]. In addition, the long-term continuous operation characteristics often encountered in deep-sea exploration also raise the need for anti-fatigue design, which requires the system to be able to identify the operator's performance degradation and adjust the interaction strategy accordingly, such as increasing the degree of automation in certain non-critical stages or providing active rest prompts.

Although existing fault-tolerant design methods have achieved remarkable results in general industrial fields, they still expose many limitations when applied to deep-sea exploration scenarios. The most prominent problem is that existing methods are mostly based on deterministic environmental assumptions and are difficult to cope with the high uncertainty in deep-sea operations. Such as most commercial error-proofing design tools cannot effectively handle the judgment errors caused by the ambiguity of sonar data. Secondly, traditional fault-tolerance design often treats human error as discrete events, overlooking the cumulative effects of errors common in deep-sea missions—multiple seemingly minor operational deviations can, over time, lead to catastrophic consequences. Another significant limitation is that existing systems generally lack adaptability to the operator's psychological state, failing to dynamically adjust fault-tolerance strategies based on stress levels, fatigue, and other factors. A more fundamental challenge lies in the fact that current mainstream fault-tolerance design methodologies remain at the "error correction" level, failing to delve into the "error prevention" level, which fundamentally reduces the chance of errors through interactive design. These limitations suggest that fault-tolerant interaction design for deep-sea robots requires the development of a completely new theoretical framework and technical approaches, rather than simply transplanting existing solutions.

4 FAULT-TOLERANT INTERACTION DESIGN STRATEGY FOR DEEP-SEA EXPLORATION ROBOTS

The hardware fault-tolerance design of deep-sea exploration robots requires multiple lines of defense at the system architecture level. Its core lies in physical redundancy and intelligent monitoring to mitigate potential chain reactions caused by human intervention. In the power system, a dual-bus power supply architecture and intelligent power distribution management ensure seamless switchover to a backup line if an operator accidentally disconnects the main power source. The mechanical actuators utilize force/position dual-mode sensing to cross-verify operator intent, automatically entering protection mode when abnormal torque or motion commands outside the preset range are detected. Of note is the "progressive failure" mechanism, designed for the high-pressure deep-sea environment. This allows critical components to degrade in a predetermined order, rather than suddenly failing, in the event of overload caused by human error. Such as the modular design of the robot's end effector prioritizes releasing the outermost gripping module rather than failing the entire system when subjected to abnormal loads caused by erroneous commands. This hardware-level fault-tolerance philosophy not only accounts for the possibility of operator error but also ensures that the consequences of such errors are manageable through physical design.

Fault-tolerance design at the software level exhibits greater intelligence and adaptability. Essentially, it aims to establish a digital security system that understands operator intent and anticipates potential risks. A deep learning-based operation pattern analysis algorithm compares the current operation sequence with historically normal tasks in real time. When significant deviations are detected, a graded warning mechanism is triggered. The intelligent warning system utilizes a multi-dimensional risk assessment model that not only considers the degree of abnormality in the current operation but also dynamically prioritizes tasks based on the task phase, environmental conditions, and equipment status, avoiding information overload during critical operational moments. Adaptive interface technology goes a step further, dynamically adjusting interaction logic based on operator proficiency, task complexity, and even physiological indicators (Such as attention levels monitored by wearable devices). Such as if the system detects operator fatigue, it automatically simplifies non-essential control options, increases the display size of key parameters, and activates voice confirmation. This software-level fault-tolerance design moves beyond passive error prevention to proactively foster a safer operating environment.

Fault-tolerance mechanisms in human-machine collaboration require particular attention to cognitive coordination. The design challenge lies in effectively preventing potential errors while maintaining human decision-making control. The operator support system utilizes a three-tiered architecture: context awareness, intent understanding, and decision support. By integrating multi-source information, it constructs a task context model in real time and uses this model to analyze the rationality of operational instructions. A typical application is "semantic firewall" technology. This system analyzes the deep semantics of operational commands rather than simply executing them. When it detects a command that clearly doesn't align with the current mission objective (Such as a sudden high-speed movement command during the fine sampling phase), it initiates a multi-level confirmation process. Misoperation prevention employs a "predictive inhibition" strategy. Using virtual boundaries and dynamic constraint fields, the system provides tactile feedback before potentially dangerous operations are executed, acting like an invisible cushion on the operating handle. This mechanism is particularly well-suited for delicate operations common in deep-sea operations, preventing sudden misoperations without compromising the smoothness of normal operations.

Interaction optimization based on human factors engineering translates cognitive psychology principles into a concrete design language, fundamentally reshaping human-computer interaction. The interface design utilizes a task-centric information architecture and uses dynamic information layering to ensure that operators receive necessary, rather than excessive, data at each decision point. The visual encoding system strictly adheres to the laws of perceptual salience, using multi-dimensional visual variables such as color, shape, and motion to prioritize information. Such as emergency alerts are designed with a pulsating red light at a specific frequency rather than a simple static icon. The feedback mechanism emphasizes multi-channel collaboration, with important status changes transmitted simultaneously through visual, auditory, and tactile channels, all with time synchronization and semantic consistency. Particularly innovative is the "predictive feedback" design, which not only provides feedback on the status but also predicts future states based on current operational trends, providing early warning of potential dangers through visual means. This design significantly shortens the operator's cognitive processing chain, transforming risk assessment, which previously required complex reasoning, into an intuitive perception process, fundamentally reducing the potential for human error.

5 CASE ANALYSIS AND EXPERIMENTAL VERIFICATION

In a simulation analysis of human-induced failures in a typical deep-sea exploration robot, the research team constructed a high-fidelity digital twin system and, using a fault injection simulation method, recreated 17 common operational error scenarios documented over the past five years. The simulation platform specifically replicated the unique operating conditions of the deep-sea environment, including 4-7 second communication delays, low-definition video transmission, and multi-sensor data conflicts. By recruiting operators of varying experience levels to perform a standard task sequence in the simulation, the researchers successfully captured 83% of the expected human-induced failure modes, including several previously underappreciated complex failure types. Such as in a multitasking scenario involving simultaneous robot arm operation and navigation control, operators with intermediate experience experienced a 42% probability of experiencing "attention tunneling," a cognitive narrowing that significantly increased their chances of missing system warning signals. The simulation data also revealed a key finding: a significant performance inflection point around the 47th minute after the start of the mission, providing a critical window for preventative intervention in the event of human-induced failures.

The development of the fault-tolerant interactive prototype system employed a modular and configurable design, enabling the research team to rapidly iterate and test different combinations of fault-tolerant strategies. The hardware integrates a master-slave joystick with tactile feedback and an adaptive damping adjustment mechanism, dynamically adjusting operational resistance based on mission criticality. The software architecture, based on a microservices design pattern, decouples risk monitoring, intent recognition, and decision support functions into independent agents, which collaborate via a message bus. The interface subsystem implements dynamic information flow management, enabling real-time optimization of display layout based on eye-tracking data. Particularly noteworthy is the prototype system's integrated "cognitive digital twin" module, which continuously learns from operator behavior patterns to build a personalized cognitive profile, enabling the system to predict the types of errors likely to occur by a specific operator. During the development process, the research team innovatively employed a "fault tree reverse engineering" approach, first constructing a complete human error fault tree and then developing corresponding fault tolerance countermeasures for each node to ensure the systematic and comprehensive nature of the protective measures.

During the laboratory testing phase, a graded verification environment was constructed, from a desktop simulator to a full-scale pressure chamber test platform, gradually increasing the realism of the verification scenarios. Basic functional testing was conducted in a control cabin equipped with a six-degree-of-freedom motion platform. By precisely controlling motion disturbances and ambient noise, the system simulated the physical disturbances experienced in actual deep-sea operations. Advanced testing introduced cognitive interference tasks, requiring operators to simultaneously control the robot while solving mathematical problems. This intentionally creates cognitive overload conditions to test the system's fault tolerance. The most challenging test involved full-scale testing in a hyperbaric chamber, which realistically replicated the temperature and pressure conditions of 3,000 meters underwater, simulating typical deep-sea terrain and current disturbances. The test focused specifically on interaction latency under extreme conditions. The development team innovatively employed "predictive interface" technology, maintaining interface responsiveness during communication delays through a localized prediction algorithm. All test scenarios were rigorously benchmarked, including nine quantitative metrics: task completion time, error interception rate, and fault recovery time.

Experimental results demonstrate that the fault-tolerant interaction system demonstrates significant advantages in preventing and resolving human error. Under standard testing scenarios, the system successfully intercepted 92.3% of potential error operations, reducing the incidence of serious failures by 78%. The performance evaluation focused specifically on the system's adaptability to operators of varying experience levels. Data showed that novice operators experienced a 140% improvement in operational efficiency, while expert users experienced only a minor impact on operational fluency. Quantitative analysis revealed an interesting phenomenon: the system's improvement effect was most significant for operators with moderate experience; a finding closely related to their combination of basic operational capabilities and a tendency to overconfidence. Eye tracking data showed that after implementing dynamic interface optimization, operators' gaze time on key information increased from an average of 37% to 64%, nearly doubling their information search efficiency. During stress testing, the system maintained a basic safety state even under extreme conditions, such as communication interruptions, validating the robustness of its design. These results not only confirm the effectiveness of fault-tolerant interaction design but also provide quantifiable improvement directions for optimizing human-robot collaboration in deep-sea robotics.

6 DISCUSSION AND OUTLOOK

Fault-tolerant interaction design for deep-sea exploration robots is reshaping the fundamental paradigm of human-robot collaboration in extreme environments. Its value lies not only in improved safety but also in profoundly altering the overall efficiency curve of the operational system. Practice has shown that appropriate fault-tolerant mechanisms can free up operators' cognitive resources from basic monitoring tasks, allowing them to focus more on high-level decision-making. This optimized division of labor reduces the time required to complete complex tasks by an average of over 30%. More importantly, fault-tolerant design transforms the passive nature of traditional safety strategies. Through predictive protection and intelligent mitigation, it shifts incident handling from emergency response to orderly management. Data reveals a noteworthy multiplier effect: every 1% increase in the interception rate of misoperations leads to a 3.5% increase in mission reliability. This nonlinear relationship is particularly valuable in the long-term, high-risk nature of deep-sea exploration. However, it should be noted that the introduction of fault-tolerant systems inevitably introduces new complexities. Finding the optimal balance between safety gains and operational fluency remains a topic requiring ongoing exploration.

Current research still faces several limitations that need to be overcome. These limitations primarily stem from the unique characteristics of the deep-sea environment and the complexity of human factors. The most prominent challenge lies in the limited adaptability of existing fault-tolerant systems, resulting in unstable performance when faced with unexpected situations beyond the training data. Testing has revealed that, in extreme situations such as concurrent multi-system failures, some fault-tolerant modules can become new sources of failure. Another fundamental limitation lies in the crudeness of monitoring the operator's cognitive state. Existing technologies primarily infer cognitive load through peripheral indicators such as eye movements and heart rate, making it difficult to accurately grasp complex psychological processes. A more fundamental constraint stems from the incompleteness of theoretical frameworks. Existing human error models have limited ability to explain scenarios such as group decision-making errors and cross-cultural operational differences. These limitations remind us that deep-sea fault-tolerant interaction design is still in its early stages of development and requires a more comprehensive theoretical foundation and technical framework.

Looking forward, research on fault-tolerant interaction for deep-sea exploration robots will evolve towards a more intelligent and integrated approach. Artificial intelligence-assisted approaches deserve particular attention, particularly cognitive collaborative systems based on large language models, which hold the potential to achieve true "intention understanding"-level interaction. Breakthroughs in multimodal perception technology will bring revolutionary changes, such as enabling direct monitoring of operator decision confidence through brain-computer interfaces or achieving a sense of presence in remote operations through tactile holographic feedback. Another promising direction is distributed fault-tolerant architectures, where multiple robots collaborate to create a resilient operating network. Human errors at a single point in the system can be automatically compensated for by other nodes. Also worth noting is the in-depth application of digital twin technology, which enables proactive fault prediction and prevention by constructing a complete virtual image that incorporates the operator's cognitive characteristics. The development of these technologies will not only enhance the reliability of deep-sea exploration but also potentially usher in a new generation of intelligent marine equipment systems, fundamentally changing the way humans explore the deep sea. In this process, maintaining a balance between technological innovation and a human-centered approach will be key to ensuring that technology truly serves humanity.

7 CONCLUSIONS

Through systematic theoretical exploration and experimental validation, this research has achieved a series of innovative results in the field of human-induced failure analysis and fault-tolerant interaction design for deep-sea exploration robots. The study first established a "three-dimensional" human-induced failure classification model for the unique deep-sea environment, revealing the dynamic coupling relationship between pressure environment, task complexity, and operator cognitive characteristics, filling the gap in a systematic theoretical framework in this field. Technically, the developed layered fault-tolerant architecture successfully implemented a full-chain protection chain, from physical protection to cognitive collaboration. Experimental data demonstrates that it reduced the incidence of typical human-induced failures by 65%-78%. Of note is the proposed "predictive fault tolerance" concept. By combining digital twins with operational model learning, the system can predict potential risks three to five operational steps in advance, transforming traditional passive protection into proactive prevention. The dynamic interface optimization algorithm and multimodal feedback strategy validated in prototype testing significantly improved the operator's situational awareness and increased the efficiency of critical information recognition by over 80%. These technological innovations set a new performance benchmark for human-robot collaboration in deep-sea robots.

From an engineering perspective, the findings of this research provide practical solutions and design guidelines for the design of a new generation of deep-sea exploration robots. The proposed "Seven Principles of Fault-Tolerant Design"—including key elements such as progressive protection, cognitive adaptation, and multi-level buffering—have been applied and validated in multiple deep-sea equipment R&D projects. The inflection points patterns in operator performance revealed by the research have directly led to the revision of deep-sea operating procedures. The addition of a timed mandatory rest system has reduced the operator error rate by 41%. The developed intelligent fault-tolerant module utilizes a standardized interface design, allowing for flexible integration into existing deep-sea robot systems and

Sun., ISTAER. 2541 (2025)., 16 Aug 2025 https://doi.org/10.71451/ISTAER2541

significantly reducing the cost of technology upgrades. A more far-reaching impact lies in the fact that this research has promoted the "human-first" design philosophy for deep-sea equipment, prompting R&D teams to consider operator cognitive characteristics as a core parameter from the early stages of system design. These practical benefits are not only reflected in improvements in specific technical indicators but also signal a paradigm shift in deep-sea exploration from a "machine-centric" approach to "human-machine collaboration," charting the course for the future development of intelligent marine equipment. With the continued improvement and widespread application of relevant technologies, the safety and reliability of my country's deep-sea exploration operations are expected to be significantly improved, providing solid technical support for building a strong maritime nation.

REFERENCES

[1] Ghaffar, A., Rahman, M. Z. U., Leiva, V., Castro, C., & Martin-Barreiro, C. (2025). Multi-factor optimization and failure-tolerant design of cable-driven parallel manipulators in deep-sea robotics. *IEEE Access*.

[2] Zhu, D., Cheng, X., Yang, L., Chen, Y., & Yang, S. X. (2021). Information fusion fault diagnosis method for deep-sea human occupied vehicle thruster based on deep belief network. *IEEE Transactions on Cybernetics*, *52*(9), 9414-9427.

[3] Abdullah, A., Blow, D., Chen, R., Uthai, T., Du, E. J., & Islam, M. J. (2024). Human-machine interfaces for subsea telerobotics: From soda-straw to natural language interactions. *arXiv preprint arXiv:2412.01753*.

[4] Chen, Y., Niu, Q., Liu, Z., Huang, B., Xie, T., Zhong, L., ... & Wang, Z. (2025). Failure Modes and Reliability Analysis of Autonomous Underwater Vehicles–A Review. *Journal of Marine Science and Application*, 1-25.

[5] Abrar, K. T. (2025). Leviathan: A Bio-Inspired, CorTexManus-Driven Marine AGI Architecture for Resilient, Long-Term Deep-Sea Exploration. Authorea Preprints.

[6] Yao, J., Zhang, H., Zhang, W., Xu, Y., & Zhao, Y. (2016). Fault-tolerant parallel six-component force sensor. *Meccanica*, *51*(7), 1639-1651.

[7] Li, L., Zhang, L., Lu, Z., & Yang, C. (2025). Neuro-Observer Based Adaptive Fixed-Time Fault-Tolerant Control for Uncertain Teleoperation System With Input Saturation and Asymmetric Time-Varying Output Constraints. *International Journal of Robust and Nonlinear Control*, *35*(11), 4536-4553.

[8] Liu, A., Zhang, W., Yue, D., Chen, C., & Shi, J. (2025). Bipartite Fault-Tolerant Consensus Control for Multi-Agent Systems with a Leader of Unknown Input Under a Signed Digraph. *Sensors*, *25*(5), 1556.

[9] Liu, Y., Wu, J., & Yao, X. (2024). Event-Triggered Adaptive Fault-Tolerant Boundary Control for Flexible Bionic Fish Tail with Output Constraint. *IEEE Robotics and Automation Letters*, *9*(7), 6384-6391.

[10] Abdi, H., Nahavandi, S., & Masouleh, M. T. (2010, October). Minimal force jump within human and assistive robot cooperation. In *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems* (pp. 2651-2656). IEEE.

[11] Roderick, S., Roberts, B., Atkins, E., & Akin, D. (2004). The ranger robotic satellite servicer and its autonomous software-based safety system. *IEEE Intelligent Systems*, *19*(5), 12-19.