Underwater Robot-Assisted Deep-Sea Smart Cage

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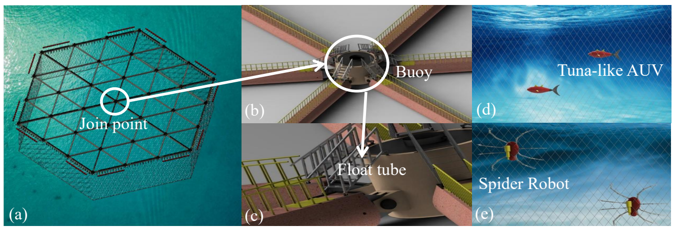

Fig. 1. System architecture. (a) Multi-chain flexible floating cage. (b) Details of the buoy. (c) Details of the float tube. (d) Tuna-like AUVs are on patrol. (e) Spider robots are mending cages.

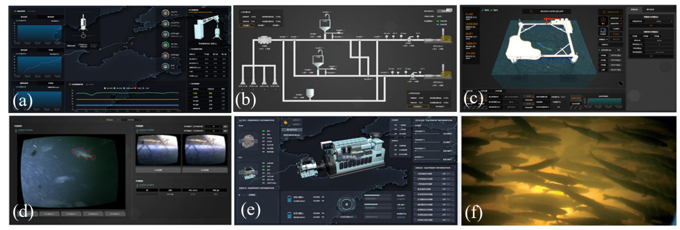

Fig. 2. Functionalities of modular intelligent operating system.

I. Introduction

Deep-sea aquaculture is an important development direction in modern fisheries, primarily due to the severe ecological challenges faced by nearshore areas such as bays and intertidal zones, including pollution and ecological degradation, necessitating a shift towards broader and ecologically healthier deep-sea regions [1], [2]. Moreover, the complex environment of the deep sea, such as high waves and strong wind conditions, also requires higher technical standards. Currently, deep-sea aquaculture mainly adopts the method of cage farming [3]. However, traditional cage systems face several issues, including low automation levels, weak resistance to wind and waves, and low comprehensive utilization of resources. With the emergence of autonomous underwater vehicles (AUVs) and underwater robots [4], [5], designing an smart aquaculture cage system based on these technologies has become a research hotspot, but no elegant solution has been found.

In this paper, we innovatively propose a deep-sea smart cage system based on a variety of self-developed underwater robots. The system is based on a multi-chain flexible floating cage that is resistant to wind and waves, and is supported by several self-developed AUVs inspired by tuna and several spider robots to maintain the cage and monitor the ecology inside the cage. At the same time, we also develop a modular intelligent operating system to realize intelligent autonomous inspection, remote perception and intelligent control of the cage. For more details, please turn to our website https://sites.google.com/view/icraworkshop1.

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II. Design of Underwater Robot-Assisted Deep-Sea Smart Cage

A. System Architecture

Our underwater robot-assisted deep-sea smart cage system, as illustrated in Fig. 1, employs a multi-chain flexible floating deep-sea cage (to be elaborated in the next chapter) shown in Fig. (1a) as the main structure. It is constructed of composite fiber reinforced concrete, benefiting from its flexible architecture which enables resistance against typhoons. Additionally, modular construction can be achieved through the connection points illustrated in Fig. (1a), as depicted in detail in Figs (1b) and (1c). The system also incorporates tuna-like AUVs and spider robots. The tuna AUVs are responsible for information gathering and patrol tasks, such as deterring sharks and other invasive species, as shown in Fig. (1d). Meanwhile, spider robots are assigned with responsibility of cleaning and repairing damaged sections of the cage, as shown in Fig. (1e).

B. Modular Intelligent Operating System

We design a modular intelligent operating system that enables remote sensing and intelligent control of the deep-sea smart net cage from land via long-distance wired communication using optical fibers. The system includes automated actuators, sensors, and supports remote and mobile clients. It allows for water quality monitoring (Fig. (2a)), process control (Fig. (2b)), automatic feeding (Fig. (2c)), biological monitoring (Fig. (2d)), equipment monitoring (Fig. (2e)), and lighting control (Fig. (2f)).

III. Multi-chain Flexible Floating Deep-sea Cage

The net cage we designed consists of a framework system, net clothing system, anchoring system, and safety protection system, among others. The corner floats and water surface

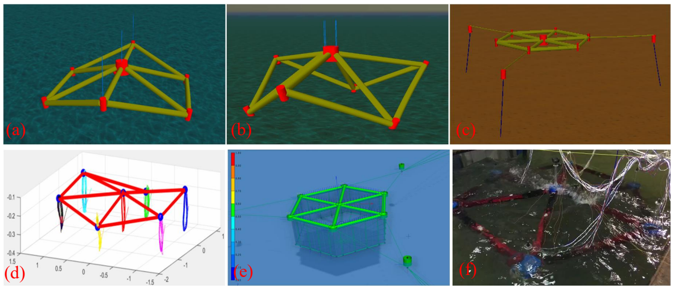

Fig. 3. Various experiments of multi-chain flexible floating deep-sea cage.

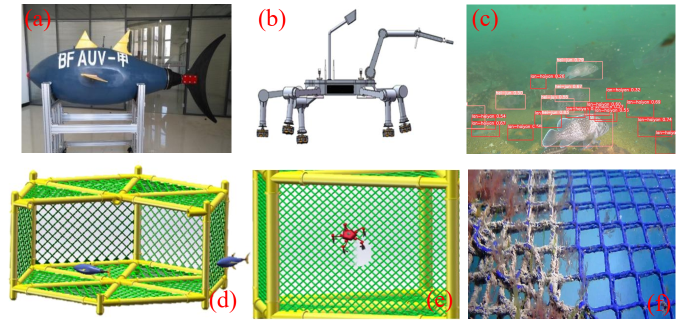

Fig. 4. The role of different robots in the deep-sea smart cage system.

rods of the net cage are equipped with pressure-displacement compartments, enabling the net cage to have a certain load-carrying capacity and achieve pressure-displacement sinking during typhoon events, thereby protecting the net cage and fish. Additionally, the hexagonal rod structure of the net cage is a flexible and deformable mechanism due to the hinge arrangement, allowing for the control of the sinking posture of the net cage according to demand, making the structure of the net cage more intelligent. As shown in Fig. (3a), if water is injected into four symmetric corner floats, the net cage can exhibit a symmetric sinking pattern resembling bird wings. However, if water is injected into the three spaced corner floats, it will result in the sinking of the three spaced corner floats and a slight sinking posture of the remaining three corner floats to maintain the geometric stability of the structure, as shown in Fig. (3b). Considering that the net cage is a symmetrical hexagonal structure, a three-point symmetrical mooring scheme (or a three-point asymmetrical mooring scheme with one main mooring point and two auxiliary mooring points adjusted according to the actual direction of the sea current, or a single-point mooring scheme) is adopted, as shown in Fig. (3c). Subsequently, we conduct simulation experiments on the net cage, as shown in Fig. (3d), and obtain static water attenuation characteristics of the net cage (floating and submerging), the horizontal stiffness of the mooring system, and stress distribution of the net cage concrete pipes through static water tests. Fig. (3e) shows the results of dynamic simulation experiments, which reveals that the net cage, with multiple stable triangles formed by the flexible floats (buoys and floats) hinged to the floating tubes, can withstand impacts as they flow with the waves. Fig. (3f) presents the results of wave tank tests, where the net cage can successfully operate under 224 different sea conditions (including severe conditions: wave height of 6m and water velocity of 1.7m/s). For example, under a typhoon of level 12, the net cage can operate normally, while under a level 14 typhoon, the net cage will submerge by injecting water, and under a level 17 typhoon, the net cage will enter a dormant state.

IV. Intelligent Management of Cage Based on Underwater Robot

To achieve automatic maintenance of deep-sea cages, such as real-time monitoring of hydrological information and fish growth, as well as net repair and cleaning, we have designed two types of underwater robots: a tuna-like AUV and a spider robot. Our tuna-like AUV (Fig. 4a) mimics the propulsion mechanism of a tuna, using its tail to achieve high-speed (24 knots), low-noise, efficient, and long-endurance underwater movement. It supports underwater wireless charging, wide-angle HD shooting (720°, 1080p), group intelligent cooperation, and underwater wireless communication. Its main tasks include biological detection (Fig. 4c) and cruise protection (Fig. 4d). The spider robot (Fig. 4b) developed by us is responsible for net cleaning and eliminating the adhesion of microorganisms using high-pressure water flow (Fig. 4f). When the tuna-like AUV detects mesh holes, it communicates underwater acoustically with the spider robots for automatic net repair (Fig. 4e).

V. Conclusion

In this paper, a underwater robot-assisted deep-sea smart cage system is designed. Firstly, the structure and modular intelligent operating system of the smart cage system are introduced. Secondly, the structure and excellent performance of the multi-chain flexible floating cage are introduced. Finally, we introduce how to realize the intelligent and automatic monitoring and maintenance of the cage with the tuna-like AUV and spider robot developed by us.

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