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Research on Cooperative Operation Control Methods for ROVs and AUVs in Constrained Waters

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Abstract - **The collaborative operation of remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) has been widely applied in the field of ocean engineering. However, there are still some issues: high latency in underwater acoustic communication, which cannot guarantee stable transmission of high-bandwidth data; erratic movement of ROV cables, leading to collision problems during the collaborative process between ROVs and AUVs; and difficulty in maintaining specific positions and orientations during collaborative operations, resulting in low operational efficiency. To address these issues, a new improvement method is proposed: adopting an underwater adaptive communication method to achieve high-bandwidth data transmission between ROVs and AUVs; adding connecting cables between ROVs and AUVs, and adopting a vision-based collision avoidance method; using an inertial measurement unit integrated with vision for pose registration between ROVs and AUVs. Experimental results show that this method reduces the time required to perform the same task by 25.67% compared to traditional schemes, providing a guarantee for the widespread application of collaborative control of underwater robots in the future.**

Keywords - ROV, AUV, cooperative control, collision avoidance, underwater adaptive communication.

I. INTRODUCTION

As marine resource exploitation and military security demands grow, ROV underwater robots have found widespread application. In marine detection and scientific research, both ROVs and AUVs serve distinct purposes. ROVs, being tethered robots, enable operators to control them remotely in real-time via cables. Conversely, AUVs are untethered robots, equipped with onboard robotic systems capable of autonomously completing preset tasks without human intervention. Given the intricate nature of the marine environment, some researchers have integrated ROVs and AUVs to enhance operational efficiency, achieving preset tasks through their collaborative efforts [1].

Communication quality significantly influences multi-robot collaboration. In literature [2], an underwater acoustic communication link is established between the ROV and AUV, with the ROV connecting to the ROV TMS through underwater acoustic communication, which in turn communicates with the ground control station via fiber-optic cables. Literature [3] adopts an underwater acoustic communication networking strategy, designing a layered communication architecture to enable information exchange and data transmission among AUVs. During the collaboration between ROVs and AUVs, the constrained data rate of underwater communication adversely affects the transmission of high-bandwidth signals. Literature [4] integrates deep learning algorithms to devise an adaptive switching and tuning method, enhancing robustness against impairments in the underwater acoustic channel. Since underwater acoustic communication networks necessitate multi-hop transmission to reach the base station, challenges such as cumulative multi-hop delays and high bit error rates emerge. To tackle this issue, literature [5] proposes a reinforcement learning-based path planning method to more efficiently gather data from various nodes of distributed sensors. The aforementioned studies employ underwater acoustic communication for long-distance data transmission, which inherently limits its data rate. In confined water areas where ROVs and AUVs operate in close proximity and require high-bandwidth data transmission, underwater wireless communication, despite offering high bandwidth and low latency [6][7], is susceptible to link disruptions and equipment malfunctions due to the complex underwater environment. Therefore, this paper selects an adaptive communication approach that combines both wireless and wired methods.

The collision problem during the collaboration between ROV and AUV is also a primary research focus of this paper. In confined water areas, the operational space for both ROVs and AUVs is restricted, and collisions may arise due to communication link failures or system malfunctions. Literature [8] proposes a cooperative hunting algorithm in a three-dimensional underwater environment and experimentally validates the effectiveness of the DRL (Deep Reinforcement Learning) framework in avoiding collisions during collaborative operations. Literature [9] utilizes a specialized topological structure in the collaborative control process, employing distributed data fusion among individual AUVs to compute the global state and maintain a safe distance between them. However, the performance of these methods declines notably in dynamically changing underwater environments. Consequently, Literature [10] adopts a deep reinforcement

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learning approach, continuously accumulating experience through reinforcement learning algorithms to enable autonomous decision-making and obstacle avoidance. Although these solutions can enhance the efficiency of underwater robot collaboration, During robot collaboration, the loss of robots may occur due to system malfunction. To address this issue, this paper proposes adding a connecting cable between the ROV and AUV. By constraining the ROV and AUV through the connecting cable, the loss of the AUV due to malfunction can be avoided.

Pose registration stands as a pivotal factor influencing the collaborative efficiency between ROVs and AUVs. Given the involvement of multiple AUVs in collaborative tasks, the absence of a unified coordinate system among them hinders the smooth execution of all coordinate-related operations during teamwork. Literature [11] employs a fusion of visual and sonar data, followed by backend data optimization, to achieve precise pose configuration. Literature [12] delves into the challenge of ensuring global consistency among multiple AUVs, proposing an AUV clustering approach for active exploration. In this method, each AUV shares environmental information, and relative pose relationships are determined through backend pose graph optimization. Literature [13] introduces a collaborative closed-loop detection strategy, where each AUV conducts multi-beam scanning, shares discovered feature descriptions with other AUVs via underwater acoustic communication, and performs pose matching based on shared observational data. The aforementioned studies primarily address pose matching in multi-AUV collaborative operations. However, in the collaborative process between ROVs and AUVs, the connecting cables of ROVs render their pose information subject to human control. Furthermore, when both types of robots perform the same task in close proximity, high pose accuracy is required, a challenge that traditional pose information sharing methods cannot adequately meet. Since IMU sensors and depth cameras are fundamental components of ROVs, with IMUs measuring attitude changes and depth cameras capturing three-dimensional coordinates, this paper integrates the physical data from these two sensors to design a position matching system characterized by robust stability and high precision.

Summarizing the aforementioned research outcomes, underwater adaptive communication emerges as the optimal solution for facilitating communication between ROVs and AUVs. Concurrently, wired communication cables can effectively prevent AUVs from experiencing loss of control during collaborative operations, while wireless communication can act as a redundant communication channel. To circumvent collision issues arising from cable entanglement during collaborative tasks, this paper proposes a collision avoidance algorithm. Furthermore, to enhance the precision and efficiency of collaborative operations, this paper adopts a sensor fusion approach for pose matching.

II. DESIGN PROPOSAL

Due to the significant attenuation of electromagnetic waves in water, traditional collaborative control schemes for Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) predominantly employ underwater acoustic communication. However, the data rate of underwater acoustic communication is approximately 69 kbps at a communication distance of 3,600 meters [14] Within the spatial range of collaborative operations between ROVs and AUVs in confined waters, despite the relatively short distances, the complex underwater environment adversely affects communication quality and poses a risk of loss of control, as illustrated in Figure 1 To address this, a communication cable approximately 3 meters in length is installed between the ROV and the AUV. Nevertheless, the addition of this cable increases the likelihood of collisions between the two vehicles. To prevent collisions and ensure the AUV system remains under control, a collision avoidance algorithm based on visual detection has been devised. This algorithm integrates depth information from a depth sensor with image data captured by a binocular camera. When the fused data falls within a predefined threshold, an alarm is activated to dynamically adjust the paths of the ROV and AUV, thereby avoiding collisions.

During the collaborative process between the ROV and AUV, their poses continuously change. To ensure mutual awareness of each other's information and achieve collision avoidance as well as overlapping working areas, this solution employs a method that combines data from an Inertial Measurement Unit (IMU) and a depth sensor for pose estimation and configuration.

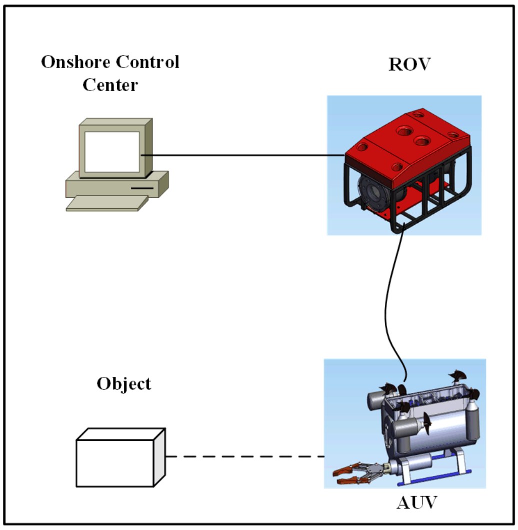

Fig. 1. Solution Structure Diagram.

III. DESIGN OF CONTROL METHOD

A. Underwater adaptive communication

There are two modes for wireless communication between ROVs and AUVs: Ad-hoc mode [15] and AP mode [16]. In Ad-hoc mode, wireless connections between all network cards of individual ROVs and AUVs do not require a third-party router for access. Point-to-point communication is achieved through wireless physical links between the network cards, as shown in Figure 2 below. In AP mode, the ROV acts as a router, and the wireless network cards in other AUVs connect to it to achieve point-to-multipoint connectivity.

The above two communication methods each have their advantages. For the Ad-hoc mode, all AUVs need to establish wireless connections with the ROV, which increases the processing load and convergence time of the ROV but

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enhances link redundancy. If any AUV fails, it will not affect the normal operation of other links. For the AP mode, if the ROV fails, all AUVs cannot work together, which directly leads to the failure of collaborative work.

Due to the extremely low bandwidth, high latency, susceptibility to interference, and multipath effects of underwater wireless communication, the disconnection of its communication link can affect underwater operations. Therefore, a wired communication link is added as an alternative communication link. As shown in Figure 3, after adding this communication link, it can be used as a backup for wireless communication: when the wired communication link is normal, this communication link is preferred for communication; when the wired communication link is disconnected, it automatically switches to wireless communication mode.

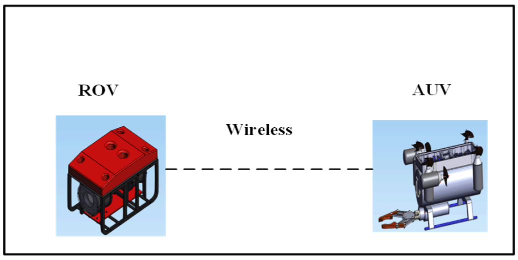

Fig. 2. Ad-hoc mode structure diagram.

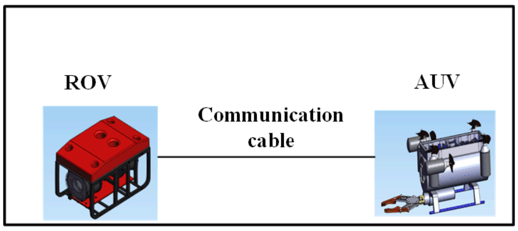

Fig. 3. Structural diagram of wired communication mode.

The algorithm design is illustrated in Figure 4. After initialization, each hardware module proceeds to the communication link selection process, which is determined jointly by the communication rate and the connection status of the communication link. The communication rate referred to in this algorithm is the average rate for sending a 100M file, while the wireless connection status pertains to the connectivity status of the wireless network card, encompassing both connected and disconnected states.

B. *Design of collision avoidance algorithm*

In the collaborative process between ROV and AUV, a connecting cable is used for cooperative control. However, when additional cables are added, the movements of the two become mutually influenced. If their relative positions are not appropriate, the connecting cables may become entangled, leading to collisions. Furthermore, with the addition of connecting cables, the movements of the robots become mutually constrained. If one of the robots loses control, it can also cause collisions between the robots. Similarly, the influence of water flow is also an important factor. If the water flow is too strong during the collaborative work of the robots, it can cause collisions among the collaborative robot groups.

To avoid collision issues in collaborative work among underwater robots, a collision avoidance algorithm based on image processing is designed. The specific algorithm is as follows: First, a camera is used to capture real-time images of the connecting cables between two devices. Then, noise is removed through image preprocessing methods. After that, the degree of curve bending is analyzed by calculating its curvature. When the curvature of the curve exceeds a certain threshold, it can be determined that a collision has occurred.

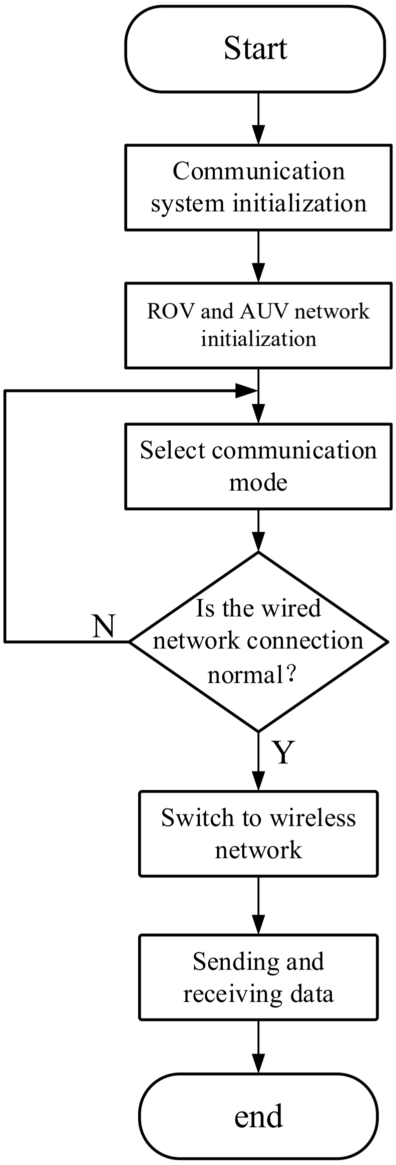

Fig. 4. Flowchart of underwater adaptive communication.

C. *coordinated control*

Collaborative robots completing specific underwater tasks serve as a crucial measure of the efficiency of collaborative control operations. In the underwater operating environment, it is crucial to have collaborative robots transport moving objects and evaluate the precision of the system control by measuring the efficiency of task completion. During the system control process, pose matching and command coordination are two important procedures.

First, determine the reference position of the underwater space. Then, perform underwater calibration on the two robots to determine their three-dimensional coordinates, as shown in Figure 5 below. By fixing the position of the ROV, the position of the target object in the ROV coordinate system A is determined. Subsequently, the position of its coordinate system in the AUV is determined through coordinate transformation.

For ROVs and AUVs during the operation process, PID and sensor fusion control are employed. Figure 6 depicts the state transition diagram of collaborative control, and the corresponding control flow is as follows: First, the ROV performs initialization and startup, and carries out depth control in the base coordinate system. Then, the ROV uses dual cameras to capture images of the target object, calculates the distance from the camera to the target object based on the SGM algorithm [17], and performs 3D modeling. Subsequently, the AUV performs pose matching to calculate the distance from the target object to itself. The AUV tracks the target by collaborating with the ROV and exchanging data in real-time. Finally, the AUV's manipulator initiates a grasping control command to perform real-time control of the target object. Throughout the entire intelligent control process, ROVs and AUVs exchange data in real-time.

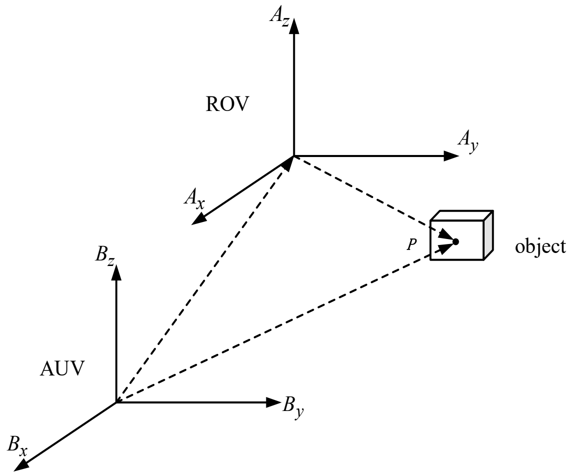

Fig. 5. Spatial coordinate system.

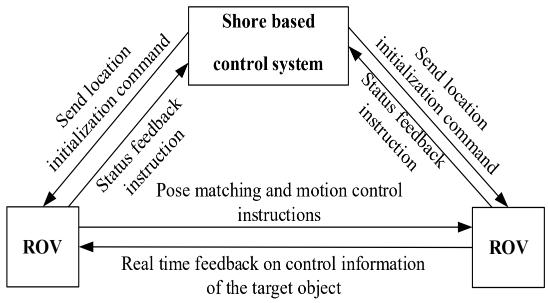

Fig. 6. State diagram for cooperative control of ROV and AUV.

IV. EXPERIMENTAL DESIGN

A. Experimental environment setup

The shore-based control system operates on Windows 11, featuring a 13th Gen Intel(R) Core(TM) i5-13500H CPU running at 2.60 GHz, an Intel Wi-Fi 6 AX201 wireless network interface controller, and Python version 3.11. The main controller for ROV and AUV is a Raspberry Pi 5B. Figure 7 below illustrates the collaborative working scenario.

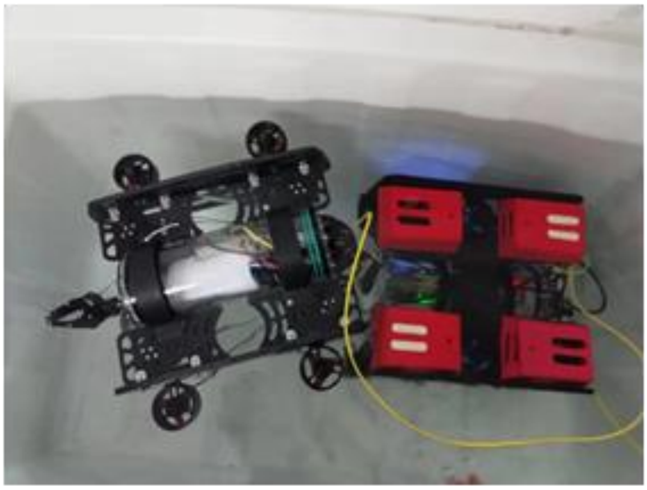

Fig. 7. Collaborative work scenario diagram.

B. Analysis of Experimental Results

To verify the effectiveness of the control method proposed in this paper, three random positions, namely P1, P2, and P3, were selected for experimentation. Each experimental setup was tested 10 times, and the experimental results are presented in Table 1. The experimental results in Table 1 indicate that the wireless transmission delay is relatively small through the wireless adaptive communication method. Based on this communication method, the underwater robot collision avoidance algorithm is implemented. Figures 8 and 9 depict color and grayscale images of the connecting cable captured by the ROV camera. The curvature is calculated through image processing methods. When the curvature exceeds a certain threshold, a motion command in the opposite direction is sent to the AUV to avoid collision.

Figure 10 illustrates the rotation parameters of the AUV at a specific moment during its operation. These parameters indicate that the AUV is in a stable state. To assess the stability of the ROV during operation, this paper uses the depth as an evaluation metric. The data presented in Figure 11 demonstrates that the depth remains around 43CM during operation, indicating high stability.

Table 2 presents the experimental results of the collaborative control between ROV and AUV for grasping underwater target objects, with each experimental result being the average of five trials. The experimental results indicate that, compared to the schemes of a single ROV, a single AUV, and the collaborative work of ROV and AUV, this scheme adopts an adaptive communication mode with lower transmission delay and higher stability; employs a collaborative work scheme and designs a collision avoidance algorithm to effectively reduce the probability of collisions; and the control of collaborative work in this scheme requires no manual intervention, with the average time taken to complete the task being 25.67% less than that of the individual ROV and individual AUV, and the success rate of collaborative operation being 100%.

TABLE I. EXPERIMENTAL RESULTS OF UNDERWATER ADAPTIVE COMMUNICATION

Experimental Group	Communication Method	Test Message	Average Response Time
1	Ad-hoc	32 Byte	20
2	AP	32 Byte	25
3	Auto mode	32 Byte	3

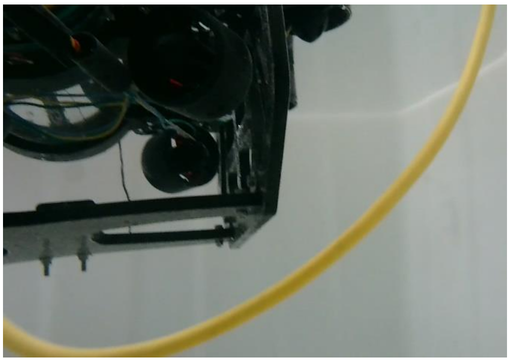

Fig. 8. Collision detection image.

Fig. 9. Image for curvature calculation.

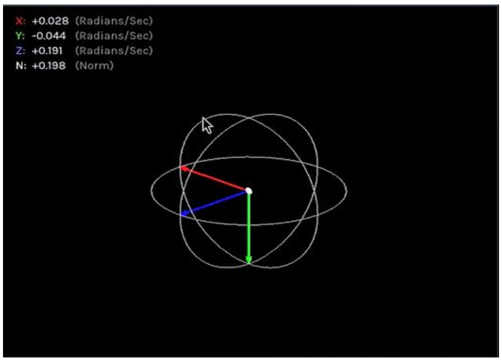

Fig. 10. Rotation parameters of a 3D space ROV.

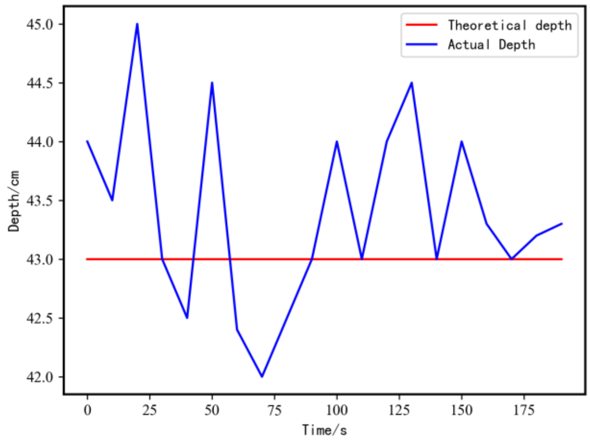

Fig. 11. Stability test results.

TABLE II. EXPERIMENTAL RESULTS OF THE CONTROL METHOD PRESENTED IN THIS PAPER

Experimental Group	Testing Method	Test Results	Test Duration
1	A single ROV	Success	58
2	A single AUV	Success	55
3	This proposal	Success	42

V. CONCLUSION

This paper adopts underwater adaptive communication methods to enhance the stability of communication. It adds connecting cables between ROVs and AUVs, and designs collision avoidance algorithms to reduce the probability of collisions. Experimental results show that this scheme provides better stability and higher efficiency than operations conducted by a single ROV or AUV, and can serve as a reference for underwater multi-robot collaborative control.

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