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RESEARCH ARTICLE

Cooperative Control of Multiple Underwater Robots Based on Brief Binary Optical-Acoustic Dual Signals

HUIYU ZHANG[1], LU LIU[1], CHENYU YANG[1], ZHIYI YANG[1], QI WANG[1], BIN YAO[1], ZENGXING ZHANG[2], XIN WANG[1], XILING SHI[1], DAN LIU[1], AND CHENYANG XUE[1]

[1]State Key Laboratory of Dynamic Measurement Technology, North University of China, Taiyuan 030051, China
[2]Pen-Tung Sah Institute of Micro-Nano Science and Technology, Xiamen University, Xiamen 361102, China

Corresponding author: Dan Liu (liudan235@nuc.edu.cn)

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ABSTRACT The applications of multiple underwater robots are becoming more widespread as the oceans continue to be explored. However, the cooperative control of multiple underwater robotic systems lacks an effective way to interact with information in the presence of weak communication in the water. This study proposes a brief binary optical-acoustic dual signals hybrid cooperative control method for overcoming this difficulty. It simplifies the information interaction rule to improve the efficiency of cooperative control while guaranteeing the range of underwater communication. This method includes an acoustic communication mechanism that enables the underwater robot to transmit signals over long distances and an optical communication mechanism that enables the transmission of signals in close situations. Avoiding information redundancy due to traditional underwater real-time communication, the underwater robots send brief binary signals through optical and acoustic sensors to realize cooperative control. An underwater robot equipped with a dual optical-acoustic system is designed in this paper combining the leader and follower formation structure. The triangular formation experiment and diamond formation experiment were also conducted in the pool to verify the effectiveness of this cooperative control method. The study provides a method for the cooperative control of multiple underwater robotic systems.

INDEX TERMS Multiple underwater robots, information interaction, brief binary optical-acoustic dual signals, cooperative control method.

I. INTRODUCTION

Underwater robots have become the most effective tools in developing and utilizing marine resources. As early as the 20th century, underwater submersibles were the most studied underwater robots globally [1]. A single underwater robot has various drawbacks such as limited task completion, high power consumption, and low efficiency when it comes to complex underwater tasks. In contrast, multiple underwater robotic systems are highly robust and allow for multi-tasking and more flexibility, which have used in underwater surveys, underwater search, rescue, navigation, and many other areas [2], [3], [4], [5]. Cooperative control has received widespread attention as the key to efficiently carrying out tasks with multiple underwater robots. And the underwater weak communication environment leads to the lack of effective interaction between individual multi-underwater robots [6]. Therefore, there is an urgent need to develop an effective way to interact with information between underwater multi-robot individuals.

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Normally, high frequency radio, Bluetooth, infrared and other communication methods are widely used in multi-robot systems [7]. Airborne swarms of small robots have achieved higher precision of group coordination and formations in dense and complex environments [8]. They rely on electromagnetic waves for information interaction. However, studies have shown that underwater communication conditions are more demanding than traditional land and air communication methods. Wireless communication methods such as wireless electromagnetic waves are more severely attenuated underwater. Underwater acoustic wireless communication [9] and underwater wireless optical communication [10] are the main wireless communication mode used underwater. Sound waves have long wavelengths and can travel thousands of kilometers in the ocean. The long-distance transmission characteristics of sound waves have been widely used in underwater multi-robot communication [11], [12], [13]. However, when acoustic waves are used for underwater communication, the channel bandwidth is narrow, and the signal frequency available is basically around 20 kHz. Furthermore, acoustic waves propagate in the form of mechanical vibrations in multiple directions, which are prone to multi-path effects and make the propagation unstable. Moreover, the propagation speed of water sound is only 1500 m/s, which has high delay [14]. Another underwater optical communication technology can be used to overcome the defects of underwater acoustic communication, including narrow broadband, the large impact of environmental noise, the low applicable carrier frequency, and a large transmission delay. The absorption of 400 $\sim$ 600nm wave band is much lower than that of other wavelengths in the seawater environment. The blue-green light provides the condition for underwater wireless optical communication. The European Union's CoCoRo project realized group recognition and self-awareness of the underwater robots by using blue-green light in three heterogeneous groups for monitoring [15] and searching [16]. However, the propagation distance of light is greatly limited by the turbidity of underwater [17]. As a solution, researchers have conducted formation experiments using soft robot fish schools [18] and spherical robots [19], [20], [21], [22] by acquiring relative position and attitude using binocular vision. Still, the limited formation distance caused by the robot's visual range underwater is yet to be overcome [23]. Therefore, the lack of efficient communication methods underwater is the main reasons limiting the development of cooperative technologies for multiple underwater robots. Relying only on a single communication method can no longer meet the future development trend of cooperative tasks of multiple underwater robots. In ocean exploration, a kind of novel Optical-Acoustic hybrid Underwater Wireless Sensor Network has been proposed. This scheme realizes high-speed transmission of optical and acoustic links by deploying multiple nodes on the seabed for networking in order to transmit ocean detection information in real time [24]. This optical-acoustic networking improves communication efficiency. However, fixed and limited networking ranges, expensive construction costs and complex communication protocols are impractical in underwater multi-robot systems. For cooperative control of multiple underwater robots, real-time connections between individuals are not required. On the contrary, a simple and efficient optical-acoustic hybrid communication method is more meaningful.

In this article, a method of brief binary optical-acoustic dual-signal hybrid cooperative control is proposed. Relevant communication tests are conducted using low-cost, small-sized multi-sensors, and an underwater robot is designed based on the formation structure of a leader and a follower to form a formation strategy based on optical-acoustic dual-signal hybrid communication. The pool experiment provides a feasible solution to the current challenge of cooperative control of underwater robots.

This article is divided into five sections. Section II introduces the small underwater robot system, including the structure and hardware composition of the robot. Section III covers the design and construction of the brief binary optical-acoustic dual-signal hybrid cooperative control system. The optical and acoustic communication system of the robot is described, and the advantages of this cooperative approach are demonstrated here. Section IV discusses the formation strategy of multiple underwater robots, the related pool experiments, and the results. Finally, a summary is presented in Section V.

II. SMALL UNDERWATER ROBOTS

A. THE MECHANICAL STRUCTURE DESIGN OF A SMALL UNDERWATER ROBOT

An underwater robot with optical-acoustic dual-signal hybrid control is designed by integrating the ability to possess multiple sensor positions, underwater power, and ideal size. The main structure of the robot is shown in Fig.1. The robot is 18 cm long, 13.5 cm wide and is symmetrical. It consists of a hull, four propellers, an electronic system and a mobile power supply. The design is ideal for the assembly positions of the photoelectric sensors and LEDs of underwater robots. As the only light-sensitive surface, the photoelectric sensor has the inherent characteristic of different angles of light corresponding to different voltage signals. The head and tail of the robot are ellipsed, the head is equipped with a photoelectric sensor, and the tail is equipped with Blue LEDs as a light source, which is distributed in all directions in a semi-arc shape.

Consequently, the robot can use the light signal to identify robots in front. In addition, it can use the voltage values sampled in real-time from the photoelectric sensors in the front half of the body to compare the position of the light source and determine the orientation of other robots. The mounting position of the photoelectric detector is adapted to the structure of an equal-sized groove. In other words, the mounting positions of photoelectric sensors are made of equal-sized grooves, whereas the LEDs mounting positions are made

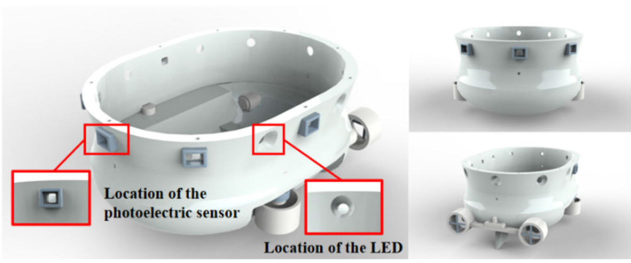

FIGURE 1. The main form structure of the underwater robot.

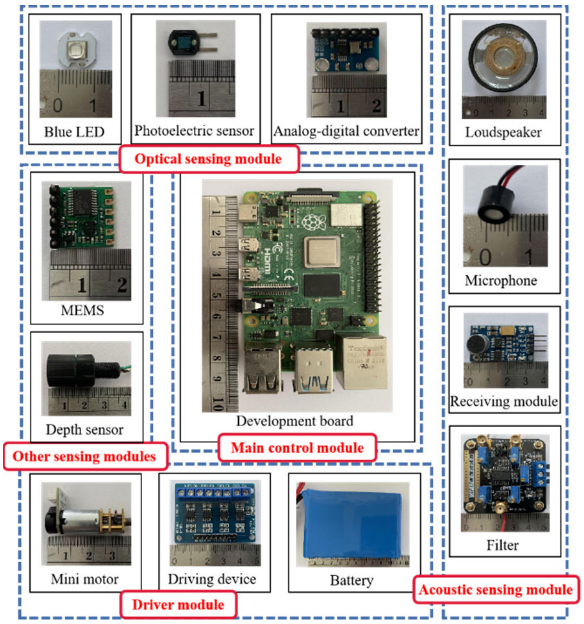

FIGURE 2. The electronic modules of the underwater robot.

of an open-120° tapered structure. In addition, because the sound sensor can receive an omnidirectional sound signal in the water, it is fixed directly in front of the robot. The robot can effectively carry optical-acoustic sensors, which provides an experimental platform to verify the underwater optical-acoustic dual-signal hybrid cooperative control method.

B. THE ELECTRONIC SYSTEMS OF SMALL UNDERWATER ROBOTS

The main electronic system's design needs to consider modularity and miniaturization. The electronic system mainly consists of a main control module, an optical sensing module, an acoustic sensing module, a driver module, and a power supply module. The details of the electronic system and each module are shown in Fig.2.

Raspberry Pi is selected as the main control board of the robot to facilitate surface debugging and future functional expansion. The Raspberry Pi is equipped with the Linux operating system. The multi-sensor fusion control closed-loop algorithm was completed in the Linux system, including optical and acoustic sensing data fusion and attitude angle fusion power regulation. VNC was used to connect and debug with the host computer to avoid frequent assembly and debugging of individual robots. Each robot became an independent underwater system after the commissioning of the host computer.

The optical source uses bright LEDs with advantages like fast switching, low cost, and are small. Blue LEDs and Photoelectric sensors were selected for communication in the underwater environment. The driver board drove the sound source after tuning the frequency to drive the loudspeaker. The microphone and filter realized the receiver side. The MEMS inertial sensor provided the robot motion attitude angle, and the depth sensing module took the depth value to control the motor motion through the closed-loop PID algorithm. A four-paddle propulsion device propels the robot. The double paddles at the tail ensure the robot can move differentially horizontally to complete forward, backwards, and turning movements. The double-side paddles ensure vertical movement, which could achieve surfacing, diving, and hovering in the water. A large enough mobile power supply powered the whole system.

III. BRIEF BINARY OPTICAL-ACOUSTIC DUAL-SIGNAL HYBRID COOPERATIVE CONTROL

Many researchers now develop swarm algorithms based on nature-inspired and use them in underwater multi-robot systems. However, the implementation of these cooperative control algorithms requires a large amount of communication between underwater intelligences [7]. Thus, the cooperative control problems in underwater multi-robots all originate from the dependence on communication.

To reduce the impact of underwater communication, this paper proposes a cooperative control method for underwater brief binary optical-acoustic dual-signal hybrid. A combination of underwater long-range acoustic signal transmission and near range optical signal transmission is used to improve the control efficiency of multiple underwater robots. The robots send binary codes with smooth and intermittent optical-acoustic dual signals to simplify the interaction principles. In order to complete the optical-acoustic dual-signal transmission system for the robots, two communication methods, optical and acoustic, are designed and experimented respectively.

A. DESCRIPTION OF THE COOPERATIVE CONTROL METHOD

No obvious information exchange between individuals is required for the behaviour of many underlying collaborative instructions between underwater robots, which can be achieved using simple interaction rules with local sensing from sensors. The transmitted information is simplified, split, and binary-coded to improve the efficiency of the underwater cooperative. Using the presence or absence of optical and acoustic signals for communication, the complex communication between underwater robots is transformed into a fast, simple and reliable "code word". For example, the binary numbers 0 and 1 represent the beacon light going off and on,

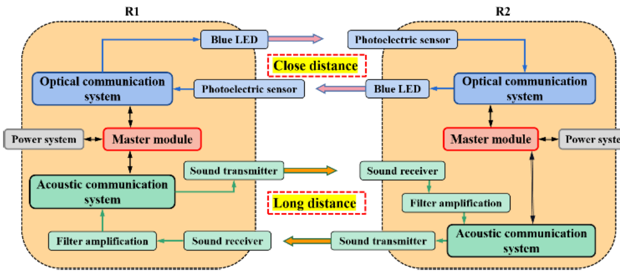

FIGURE 3. Schematic diagram of optical-acoustic dual-signal hybrid communication for underwater robots.

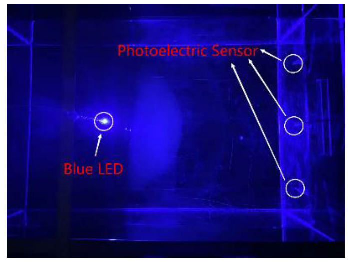

FIGURE 4. An experimental setup for measuring light-sensitive distance.

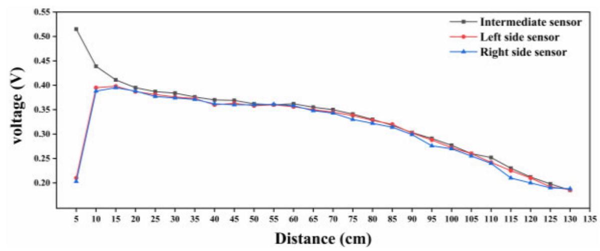

FIGURE 5. Results of the experiment generated from the measurement of light sensitivity at different distances.

respectively. The robot receiving the signal can convert the received light signal into a binary code.

R1 and R2 are two underwater robots of the same configuration. The distance is determined to be long range when it is below the optical signal transmission threshold, and the signal is transmitted through the sound module. A large and diverse amount of inter-individual information transfer is required in the case of close clustering for rapid cooperative control. At close range, introducing an optical channel not only enriches the data that can be transmitted and expands the communication bandwidth but also avoids conflicts with the commands and answers of the acoustic channel (Fig.3). Therefore, underwater robots use a mixture of light and sound to form information perception and interaction between individuals.

B. THE OPTICAL COMMUNICATION MECHANISM

The underwater robot is considered to complete the validation of a brief binary optical-acoustic dual-signal hybrid control method in an experimental pool. The robot chooses to use bright LEDs as light source. Due to the nature of underwater wireless optical transmission, the robot chooses blue bright LEDs for communication [25]. While the robot autonomously controls the LED to send signals within the effective distance, the other robot receives signals using photoelectric sensors. The photoelectric sensor outputs an electrical signal based on the real-time change of its built-in photoresistor, which then becomes a digital signal after passing through the A/D conversion module. A test was conducted in a water tank to investigate the photosensitive distance and calibrate the effective range of communication using blue LEDs and photoelectric sensors to exclude the real-time influence of external underwater light on the photoelectric sensor and the interference of a few light reflections. Briefly, blue LED and three photoelectric sensors are fixed. The three photoelectric sensors are fixed at equal distances from one end of the tank. The blue LED is in the same straight line with the middle photoelectric sensor (Fig.4). The experiment expands the test range using three equidistant positions in the same plane to ensure that the photoelectric sensors in different positions of the robot can produce judgmental differences according to the light sources in different orientations. The signal strength is measured at an interval of 5 cm when the blue LED slowly moves away from the three photoelectric sensors in a straight line. The measurement results are shown in Fig.5, and the maximum transmission distance of the system with the photoelectric sensor voltage not lower than 0.2V is 120cm. The effective threshold of 0.35 V is chosen for the system to avoid the effects of light attenuation and inter-individual optical interference.

It is necessary to guarantee the reliability of the optical signal transmission and reception to achieve accurate control of the robot to complete the specified movements in the underwater environment. Therefore, "non-connected" communication protocols are used for posting or subscribing to messages across multiple bots with different roles. In this protocol, the publisher sends a message in a cycle and waits for the corresponding feedback information before proceeding to the next step. The receiver judges and analyzes the data in real-time and determines the reception as valid information before sending a feedback signal. The robots transmit messages using the LEDs' on and off for binary coding. All optical signals consist of an 8-bit binary code, which includes three check bits, one status bit, and four information bits. The calibration bits are used to determine whether the signal received by the photoelectric sensors is the correct binary code. The status bit indicates whether it is an execution state. The information bits correspond to the value of the transmitted signal. For this communication protocol, hardware tests have been conducted to simulate robot R1 transmitting blue light signals and robot R2 receiving blue light signals (Fig.6). In the Fig.6(a) and (b), this communication device has two blue LEDs fixed on the left panel. Two photoelectric sensors and four green indicators are fixed on the right panel. The blue LEDs flash to transmit information, and the photoelectric sensors receive information. The main control board decodes the information bits displayed on the green indicator. Intercept the two results of the experiment. Fig.6 (c)

TABLE 1. Comparison of interaction methods used in underwater multi-robot projects.

Project	Interaction Methods	Communication Characteristic	Data Transmission	Interaction Principle
CoCoRo [15,16]	Underwater optical communication	Short distance; Light scattering	Fast transmission at close range	Simple
EC MORPH [27,28]	Underwater acoustic communication	Long distance; Doppler principle; Noise effect	Narrow broadband; Low rate; High latency	Complex
Spherical Robots [19,22]	Underwater visual recognition	Limited range; Turbidity effect	Redundant data processing	Complex
M-AUEs [29]	Underwater RF communication	Severe attenuation; Multipath effect	Fast transmission at close range; High loss	Complex
This Work	Underwater optical-acoustic hybrid communication	Long-range acoustic signal transmission; Near-range optical signal transmission	Optical and acoustic complementarity; Binary optical and acoustic signal transmission	Simple

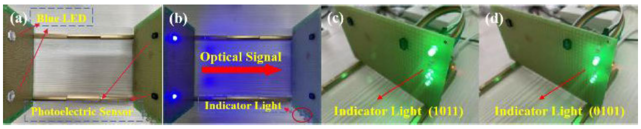

FIGURE 6. The process of receiving binary encoded information bits in the display.

shows a successfully received binary code transmitted by the blue LEDs with the information bits of 1011, Fig.6 (d) shows a successfully received binary code transmitted by the blue LEDs, and its information bits are 0101. The system transmits 24 bits of data a second. This method of simple signaling does not require large bandwidth considerations.

A threshold value is set based on the voltage variation of the photoelectric sensor affected by ambient light since the voltage value of the photoelectric sensor output varies with the ambient light at different times. To accurately define the binary value, the voltage difference between any two sensors on the robot is compared to a set threshold value. When the threshold is exceeded, the larger value is defined as a binary value of 1, and the smaller value is defined as a binary value of 0.

C. THE ACOUSTIC COMMUNICATION MECHANISM

At the same time, the underwater robot is equipped with an acoustic sensing system for information transmission over longer distances. The active unit emits the sound signal by driving a loudspeaker, and the passive unit receives the sound signal through a microphone. The passive detection signal is filtered and amplified to obtain the correct frequency signal. This experiment verifies the feasibility of sound signal transmission in the strategy.

The experiment was completed in the laboratory pool. A frequency sound of 3 kHz was selected for communication experiments [26]. Two robots equipped with sound-sensing systems were placed at different locations in the pool. One robot is used to transmit the sound signal while the other

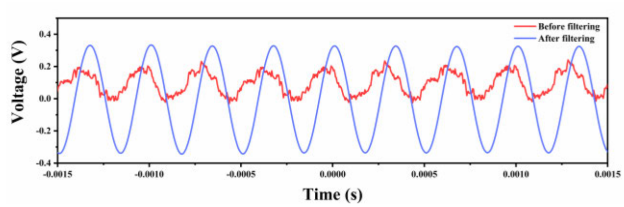

FIGURE 7. Comparison of target frequency added to the noise, the red curve is the sound signal received directly after noise interference, and the blue curve is the sound signal at 3 kHz obtained after filtering and amplification by the robot.

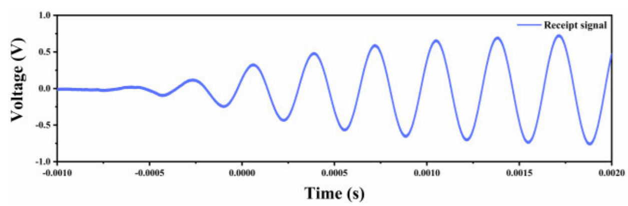

FIGURE 8. The received target frequency signal.

receives the sound signal. If the receiver side of the sound sensing system gets accurate information after signal processing, then it needs to get a smooth sound signal profile after receiving filtering. During the experiment, the stability of the signal transmitted by the sound system is tested by adding noise interference of different frequencies. The filter is a bandpass filter with a center frequency of 3khz. In Fig.7, the red curve is the sound signal received after noise interference, and the blue curve is the sound signal at 3 kHz obtained after filtering and amplification by the robot. The comparison test results show that the system can receive effective water sound signals. The robot has to analyze the sound signal by perceiving the threshold value of the sound judgment. If the reception exceeds the defined threshold value it starts to analyze the sound signal, and below the threshold value it ends the analysis. In order to define the sound threshold, the process of receiving sound signals from nothing to something is monitored. The results of Fig.8 get that the system can filter out noise signals of other frequencies before receiving the signal of the target frequency.

D. THE CHARACTERISTICS OF THIS UNDERWATER COOPERATIVE CONTROL APPROACH

There are few projects with practical applications of underwater multi robots. Table 1 shows the technical advantages and disadvantages of some excellent research projects. It is not difficult to see that the current collaborative efficiency of underwater multi-robot is limited by communication methods and interaction rules. The single communication mode determines the scope of cooperative control, and the interaction principle between individuals will affect the accuracy and efficiency of cooperative control. If the underwater communication range is guaranteed and the information transmission between individuals is compressed in an underwater multi-robot cooperative task, the cooperative efficiency will be greatly improved. This study verifies the feasibility of a brief binary optical-acoustic dual-signal hybrid cooperative control method from theory to multi-robot experiments. This work not only combines the advantages of optical-acoustic communication, but also improves the efficiency of information interaction by using the way of sending and receiving binary signals.

IV. MULTI-ROBOT FORMATION STRATEGY AND REAL VEHICLE VERIFICATION

Formation control of multiple underwater robots is a key technology for cooperative control of multiple underwater robotic systems. In the cooperative task of multiple robots, the effective geometric formation formed by the control is the basis to complete the task. The feasibility of the brief binary optical-acoustic dual-signal hybrid cooperative control method is verified by realizing the formation task of multiple underwater robots. The strategy of formation task is designed and analyzed based on optical and acoustic dual signal communication method. It is mainly divided into multi-robot position estimation and multi-robot system linkage. The formation algorithm relies on a particle swarm algorithm combined with an optical and acoustic signal feeder to form the formation motion algorithm [30], which was subsequently physically verified in the pool.

A. THE DESIGN OF THE FORMATION STRATEGY

The position expectations of triangle and diamond formation are formed according to the leader-follower formation structure. In formation tasks, the control realizes that each follower robot forms a different distance and angle from the leader robot to achieve the desired formation. The formation problem is transformed into a problem of the relationship between the follower and the leader robot [31], [32], [33], [34], [35].

The relationship between any of the follower robots and the leader robot is shown in Fig.9. (x_L, y_L) and (x_F, y_F) are the position coordinates of the leader and follower robots, respectively. φ_{L0} and φ_{F0} are the heading angles

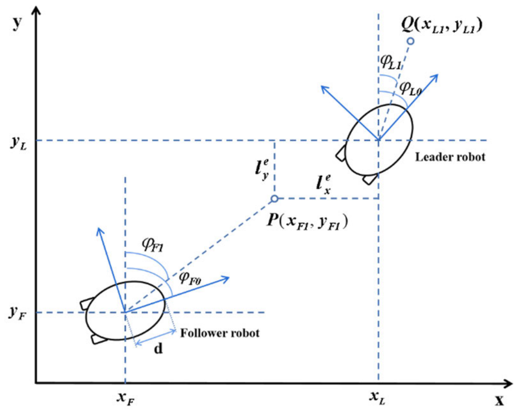

FIGURE 9. The leader-follower method.

of the pilot robot and the following robot, respectively, and d is the distance between the center of mass and the head of the robot. Accordingly, the relative azimuth angle ϕ and relative distance l between each follower and the leader robot are obtained. (1) and (2) are the formulae for calculating the relative distance and relative azimuth, respectively.

$$l = \sqrt{(x_L - x_F - d\cos\varphi_{F0})^2 + (y_L - y_F - d\sin\varphi_{F0})^2} \quad (1)$$

$$\phi = \begin{cases} \pi - \varphi_{L0} + \arctan\dfrac{x_L - x_F - d\cos\varphi_{F0}}{y_L - y_F - d\sin\varphi_{F0}}, x_L \geq x_F \\ \dfrac{3}{2}\pi - \varphi_{L0} + \arctan\dfrac{x_F - x_L - d\cos\varphi_{F0}}{y_L - y_F - d\sin\varphi_{F0}}, x_L < x_F \end{cases} \quad (2)$$

If the position of the leader robot is known, the position of the follower robot can be uniquely determined as long as the relative horizontal distance l_x and the relative vertical distance l_y between the leader robot and the follower robot are determined. To obtain the desired formation structure, it is necessary to control the relative horizontal distance, and relative vertical distance between the leader robot and the follower robot to achieve the desired values of l_x^e and l_y^e. Point P denotes the position (x_{F1}, y_{F1}) where the follower robot is located in the desired formation structure. Point Q denotes the desired path point position (x_{L1}, y_{L1}) of the leader robot. During formation construction, the desired position point Q (x_{L1}, y_{L1}) of the leader robot in the next cycle is estimated based on its current positional information (including velocity v_L, heading angle φ_{L0}, and coordinate value (x_L, y_L)). By combining the current desired formation structure (including the relative horizontal l_x^e and the relative vertical distance l_y^e), the desired position point P (x_{F1}, y_{F1}) of the follower robot in the next cycle is obtained. Then, based on the current position (x_{F0}, y_{F0}) of the follower robot, the desired average velocity v_{F^e} of the follower robot moving toward the target point (x_{F1}, y_{F1}) during the period T is calculated and v_{F^e} is set to be less than the maximum velocity v_m of the follower robot. (3) is the calculation method for multi-robot formation

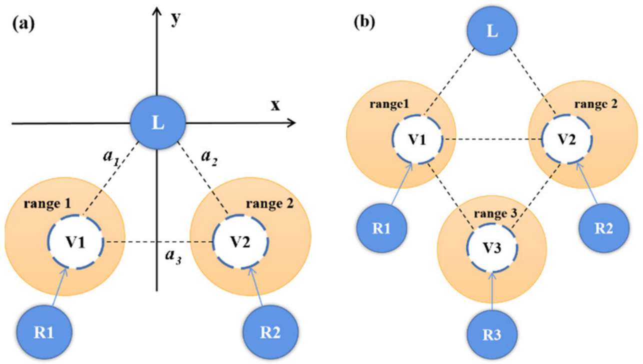

FIGURE 10. Multi-robot formation method. (a) Triangular formation virtual leader method. (b) Diamond formation virtual leader method.

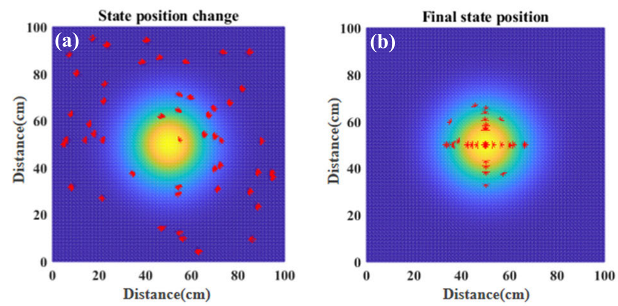

FIGURE 11. Convergence process diagram of motion controller. (a) Random particle position. (b) Convergence to light source.

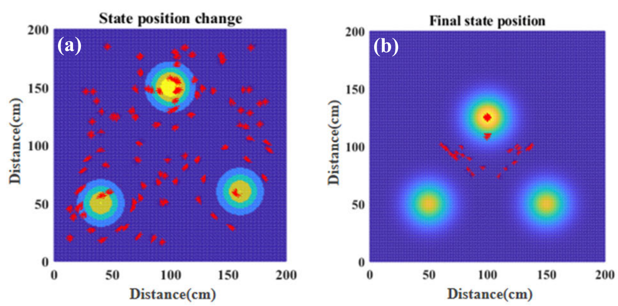

FIGURE 12. Process diagram of simulated triangular formation. (a) Random particle position. (b) Converge on the leader light source and form a triangle formation.

control.

$$\begin{aligned} x_{L1} &= x_L + v_L T \sin(\varphi_{L0}) \\ y_{L1} &= y_L + v_L T \cos(\varphi_{L0}) \\ x_{F1} &= x_{L1} + l_x^e \\ y_{F1} &= y_{L1} + l_y^e \\ v_{F^e} &= \frac{\sqrt{(x_{F1} - x_F)^2 + (y_{F1} - y_F)^2}}{T} \\ s.t. v_{F^e} &\leq v_m \end{aligned} \tag{3}$$

In nonlinear formation control of multi-robot systems, the formation control problem is transformed into a stability problem of the system error to achieve the desired formation [36]. As shown in Fig.10(a), a triangle or diamond is formed, and the leader is selected as the reference point of the formation to establish the desired range of followers. Under ideal conditions, the error formula of triangular formation is derived as in (4).

$$\begin{aligned} E(p) = {} & (a_1 \cos\theta_{13} - (x_l(p) - x_{r1}(p)))^2 \\ & + (a_1 \sin\theta_{13} - (y_l(p) - y_{r1}(p)))^2 \\ & + (a_2 \cos\theta_{23} - (x_l(p) - x_{r2}(p)))^2 \\ & + (a_2 \sin\theta_{23} - (y_l(p) - y_{r2}(p)))^2 \\ & + (a_3 \cos\theta_{12} - (x_{r2}(p) - x_{r1}(p)))^2 \\ & + (a_3 \sin\theta_{12} - (y_{r2}(p) - y_{r1}(p)))^2 \end{aligned} \tag{4}$$

In the triangle formation error formula: a_1, a_2, a_3 are the side lengths of each side of the triangle formation, and θ_{13} is the angle between the first and third sides of the triangle. Similarly, Fig.10(b) shows a schematic diagram of the diamond formation. It is easy to derive the error formula for the diamond formation. The distributed adaptive control avoids the overall communication topology dependency to stabilize the control system and reduce the formation error [37]. To stabilize the control system to reduce the formation error, the output feedback and the robot's motion algorithm are formed by relying on optical and acoustic dual signals.

Step 1: The leader's identity is determined, and the corresponding optical and acoustic signals are sent out after movement.

Step 2: The followers initialize the motion speed, and the sound influence coefficient α is defined after the followers receive the sound signal.

Step 3: The followers define β in the sensing range to determine the extreme values of their motion targets.

Step 4: The followers update the speed until the termination condition is reached.

$$\begin{aligned} x_i(t+1) &= x_i(t) + v_i(t) \\ v_i(t) &= \omega v_0 + \mu_1 [P_\alpha(t) - x_i(t)] + \mu_2 \left[P_\beta(t) - x_i(t)\right] \end{aligned} \tag{5}$$

In the follower robot's equation (5) of the motion:

x_i = the position of follower robot i
v_i = the speed of follower robot i
ω = inertia coefficient
v_0 = Initialized speed value
μ = Weight coefficient (0:1)
P = The extreme value of the moving target
α = a parameter of the optical control extremum
β = a parameter of the acoustic control extremum

The first term of the equation of motion is the initial velocity hold of the robot. The second and third terms are determined by the optical-acoustic target polarity P. Within the sensing range, the coefficient α varies according to the robot's sensing orientation, and the motion polarity varies with the sensing intensity. Outside the light-sensitive range, the robot is judged by the received sound signal, and the whole equation of motion is determined by the third term.

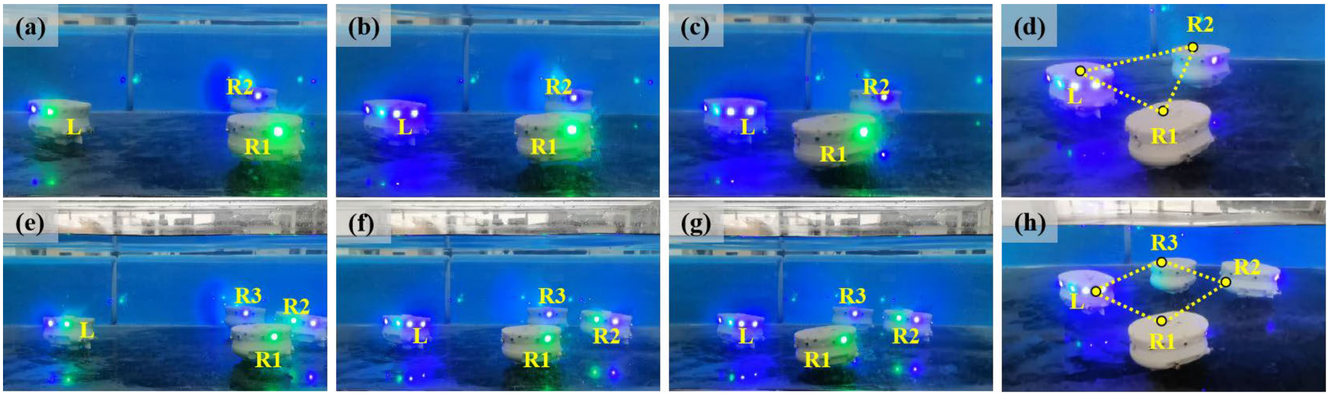

FIGURE 13. Pictures of the formation experiment. (a)-(c) Formation process of triangle formation. (d) The result of triangular formation. (e)-(g) Formation process of diamond formation. (h) The result of diamond formation.

In order to verify the convergence of this motion algorithm. Fig.11(a) shows the random position orientation to find the position of the light source in the case of the simulated robot light source. It is easy to see in Fig.11(b) that the target positions all converge at the light source. To facilitate the illustration of the stability of the photoacoustic controller in the formation system, Fig.12(a) simulates the process of finding the target robot position for two photoacoustic robots with random initial position for interference, and Fig.12(b) shows the convergence direction of the motion of the three photoacoustic simulated robots in forming a triangular formation. It can be seen that the convergence directions of both following robots are toward the pilot robot and the triangular formation is robust.

B. UNDERWATER FORMATION EXPERIMENT

The pool experiment of the underwater optical-acoustic hybrid control formation strategy has been conducted to verify the feasibility of applying the optical-acoustic hybrid system to the cooperative control of underwater robots. A large transparent pool with a black bottom, 2m long, 1m wide, and 1m deep, is selected for the experiment. Black bottom surface aims to effectively avoid the interference of reflected light from the bottom of the pool.

In the formation task, one robot assumes the role of the leader robot and the rest all act as followers. The leader robot is activated on the surface when it receives a task send from the host computer. At the same time, the follower robots turn on the acoustic system and set it to priority. After starting the task, the leader robot dives and moves to the underwater target location. The brain of the leader robot records the task command, sailing time and other information. The acoustic system is then turned on to transmit a fixed frequency acoustic signal through binary coding to send this information, and the bright blue LEDs are activated to emit blue light to attract followers. The on-call follower robots hear the same-frequency acoustic signals at a far distance, decoding and analyzing this command. The follower robots recognize the task and analyze the motion information of the leader robot and move. During the movement each follower robot receives light signals from various directions through photoelectric sensors for real-time threshold judgment. The optical system is triggered when a photoelectric sensor following any orientation of the robot reaches a threshold, and the optical system is switched to the priority. The brain of the follower robot analyzes the received light signals and recognizes the orientation of the leader robot. Then, it continuously sends its position relative to the leader robot through bright blue LEDs. The rest of the followers receive optical signals from different orientations, identifying their own position according to the formation task. Then each followers send their own position. Finally, multiple underwater robots complete the formation task. Fig.13 (a) to (c) shows the process diagram of the triangular formation experiment, where the follower robots R1 and R2 search for the leader robot L to create a formation gradually. Fig.13 (d) shows the result of creating a triangular formation. Fig.13 (e) to (g) shows the process diagrams of the diamond formation experiment. The three follower robots are R1, R2, and R3, and the leader robot is L. Fig.13 (h) shows the effect of the diamond formation.

This work is verified in the laboratory through multi-robot collaboration. Future work still needs to face new challenges for real-world applications, such as the stability of underwater optical-acoustic communication systems for sending and receiving, and the effects of water currents. This control method is not limited to this robotic system. The structure of the sensors and the robot need to be changed according to the real environment. This research is continuing and more field trials need to be conducted.

V. CONCLUSION

For solving the cooperative control problem of multiple underwater robots in underwater weak communication environment, this paper proposes a brief binary optical-acoustic dual-signal hybrid cooperative control method. The method combines the advantages of underwater optical-acoustic communication, simplifies the information interaction rules to the sending and receiving of binary signals, and improves the efficiency of information interaction between individuals. An underwater optical-acoustic robotic system was designed and a formation experiment of multiple robots was completed in a pool. The experiment used a leader and follower structure, and the triangular and diamond-shaped formations were realized by the optical-acoustic formation control algorithm. This work is verified by multi-robot cooperation in the laboratory. This brief binary optical-acoustic dual-signal hybrid control method is expected to be widely applied to improve the cooperative control efficiency of underwater multi-robot systems.

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HUIYU ZHANG received the B.S. degree in electronic information engineering from Shanxi University, Taiyuan, China, in 2020. He is currently pursuing the M.S. degree with the State Key Laboratory of Dynamic Measurement Technology, School of Instrument and Electronics, North University of China, Taiyuan. His research interests include underwater cooperative strategy and submarine control algorithms.

LU LIU received the B.S. degree in measurement and control technology and instrumentation from the Taiyuan Institute of Technology, Taiyuan, China, in 2020. She is currently pursuing the M.S. degree with the State Key Laboratory of Dynamic Measurement Technology, School of Instrument and Electronics, North University of China, Taiyuan. Her current research interest includes the formation control of multi-agent systems.

CHENYU YANG received the B.S. degree in electrical engineering and automation from the Jiangxi University of Science and Technology, Taiyuan, China, in 2020. She is currently pursuing the M.S. degree with the State Key Laboratory of Dynamic Measurement Technology, School of Instrument and Electronics, North University of China, Taiyuan. Her current research interests include underwater submersible modeling and simulation.

ZHIYI YANG received the B.S. degree in ammunition engineering from the North University of China, Taiyuan, China, in 2019, where he is currently pursuing the M.S. degree with the State Key Laboratory of Dynamic Measurement Technology, School of Instrument and Electronics. His current research interests include mechanical structure and embedded development.

QI WANG received the B.S. degree in railway signal and control from the North University of China, in 2022, where he is currently pursuing the M.S. degree with the State Key Laboratory of Dynamic Measurement Technology, School of Instrument and Electronics. His research interests include embedded systems and cooperative control algorithms.

BIN YAO received the B.S. degree in communication engineering from the North University of China, Taiyuan, China, in 2021, where he is currently pursuing the M.S. degree with the State Key Laboratory of Dynamic Measurement Technology, School of Instrument and Electronics. His research interests include embedded systems, a fusion of sensor information, and autonomous control algorithms for the unmanned underwater vehicle.

ZENGXING ZHANG received the Ph.D. degree in applied micro-and nanosystems from the University of South-Eastern Norway, Norway, in 2022. He is currently an Assistant Professor with the Pen-Tung Sah Institute of Micro-Nano Science and Technology, Xiamen University, Xiamen, China. His current research interest includes micro/nano sensors.

XIN WANG received the Ph.D. degree in armament science and technology from the Beijing Institute of Technology, Beijing, China, in 2019. He is current a Lecturer in automation with the North University of China, Taiyuan, China. His current research interest includes stability control of underwater unmanned systems.

XILING SHI received the Ph.D. degree in instrument science and technology from the North University of China, Taiyuan, China, in 2020. She is currently a Professor with the School of Electrical and Control Engineering, North University of China. Her current research interests include multi-sensor information fusion and intelligent control.

DAN LIU received the Ph.D. degree in electronic science and technology from Xi'an Jiaotong University, Xi'an, China, in 2019. He is currently a Professor with the School of Electrical and Control Engineering, North University of China, Taiyuan, China. His current research interests include underwater unmanned systems and multi-agent coordination control.

CHENYANG XUE received the Ph.D. degree in semiconductor materials from the National University of Science and Technology, Athens, Greece, in 2003. He is currently a Professor with the School of Instrument and Electronics, North University of China, Taiyuan, China. His research interests include novel micro/nano devices, solid spectroscopy, and micro-optical sensors.