Communication and Cooperation for Spherical Underwater Robots by Using Acoustic Transmission

Shuoxin Gu, Linshuai Zhang, Shuxiang Guo, *Fellow, IEEE*, Liang Zheng, Ruochen An, Tao Jiang, and Ai Xiong

***Abstract*—The application of miniature underwater robots in the marine area is becoming more extensive. Occasionally, the ability of the single miniature underwater robot is limited by its size, configuration, function or propulsion method. At this moment, if a group of robots can work together in a division of labor, that can solve more problems underwater. For autonomous underwater vehicles, the support of underwater wireless communication equipment is required to achieve communication and collaboration. Acoustic communication equipment has generally been used in large underwater vehicles due to its large size and power. This article employs a small acoustic communication module to enable underwater communication in a spherical robot with a diameter of only 45 cm. The fourth-generation spherical underwater robot is exploited as the prototype. The article also verifies the accuracy, efficiency and timeliness of the proposed underwater communication systems. Finally, a cooperative mode is established based on the base station, master robot and slave robots, and some cooperation motion experiments are carried out to verify its effectiveness. Early work on this article was presented at the IEEE ICMA 2018 conference S. Gu et al., 2018. In this conference article, the authors only provided theoretical research and a small number of experiments. On this basis, this article has conducted in-depth research, proposed a base station-mater-slave robot communication mode, and established an instruction set for further experiments.**

***Index Terms*—Instruction set, spherical underwater robots, underwater acoustic communication, underwater cooperation, underwater multicapacity communication.**

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I. Introduction

THE evolution of the exploration and discovery underwater is receiving attention in mounting numbers from mankind. autonomous underwater vehicles are used in the oceanographic study at large [2], [3]. The underwater vehicles with different configurations, sizes, propulsion methods and shapes are developed for different applications [4], [5]. With the increasing demand, more additional functions like underwater wireless communication, positioning and navigation are applied to underwater vehicles [6], [7], [8]. Common underwater wireless communication methods include electronic, acoustic, optical and laser communications [9]. Li et al. [10] in Kagawa University designed a blue LED-based underwater optical communication system for a Father-son robot system. Although the electromagnetic wave is greatly attenuated underwater, researchers in Peking University are inspired by the weakly electric fishes and designed an artificial electrocommunication system for small underwater robots [11]. The laser usually enables high-speed and long distances underwater wireless communication, Wu et al. [12] employ a 450-nm blue GaN laser diode to implement its maximal transmission capacity up to 10 Gbps. Among these underwater communication methods, the underwater acoustic communication (UWAC) with the advantages of flexibility, convenience and widespread is played more attention and used in the underwater wireless communication research. The complexity and uncertainty of the underwater acoustic channel make it the key technology of this research. Ren et al. [13] proposed an acoustic communication method with a low bit error rate (BER) which used a hybrid dynamical system to generate a chaotic signal and a corresponding chaotic matched filter to offset the effect of multipath propagation and noise. For multiuser underwater acoustic communication, the multi-chirp rate signals that can be separated by fractional Fourier transform were raised by researchers at Xiamen University [14]. For underwater acoustic communication, the boundary reflections and Doppler shift effects need to be taken into account, Gutiérrez et al. [15] present a modified Rayleigh fading communication channel model. A team of robotic boats can automate self-assemble for forming into floating platforms which will accelerate humanitarian missions or disaster relief [16]. A turtle-like underwater robot also is employed with an acoustic sensor for underwater communication and task planning [17], [18]. Another research [19] uses an acoustically controlled soft robotic fish to explore the life of underwater creatures. Although the acoustic communication module has been used by many experts and scholars in underwater robots. However, some are still in the theoretical research stage, some are used in relatively large underwater robots, and some are currently used for underwater remote control. In our previous research, the first-generation spherical underwater robot equipped with multiple vectored water jet-based thrusts was proposed at the beginning [20]. Some evaluation simulations and experiments were carried out to prove the basic motions of a prototype robot [21]. On this basis, the second-generation spherical underwater robot (SUR-II) was described by Yue et al. [22]. The hydrodynamic analysis and computational fluid dynamics simulation were conducted to obtain the estimated parameters such as the velocity vectors, pressure contours and drag coefficient [23], [24], [25]. In addition, the propulsive thrust was measured from the underwater experiments and verified the theoretical calculations and simulation results [22]. The SUR II also has an enhanced electrical and control system [26]. In the follow-up study, a father-son underwater intervention robotic system was proposed to realize underwater manipulation [27], [28]. The next development of the SUR was that Li et al. [29], [30], [31], [32] proposed the third-generation spherical underwater robot (SUR III) with four vectored water-jet thrusters. At this time, acoustic communication methods were also employed for SUR III [33]. The performance of the propulsion system for SURIII was evaluated to verify its increased stability [34]. To increase the motivation of the SUR, a hybrid propulsion system was realized in the next job [35], [36].

In this article, an UWAC system with the base station and SUR IV which is a kind of miniature underwater spherical robot is developed. The communication system was developed by using acoustic modems to realize multi-capacity communication underwater. Experiments in the tank verify the BER is 0 in a small range. Further, the experiments in the pool also proved the accuracy, effectiveness and timeliness of the communication system. To achieve the communication and cooperation of the multilevel method, the instruction set with multicapacity communication was also established. The maximum number of accommodated robots for multi-capacity is 255 in this research. Finally, the communication and cooperation experiments show that the multilevel as components of a base station, master robot and slave robot can cooperate well with each other to finish some simple tasks.

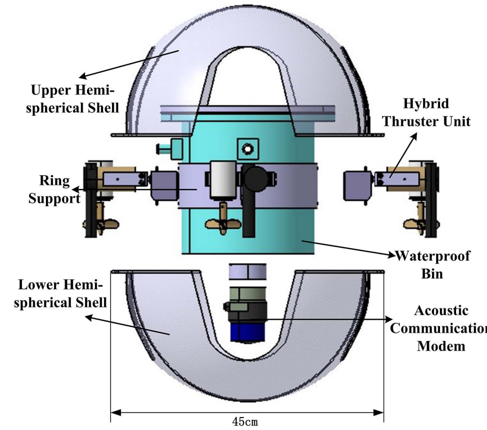


Fig. 1. Exploded view of SURIV.

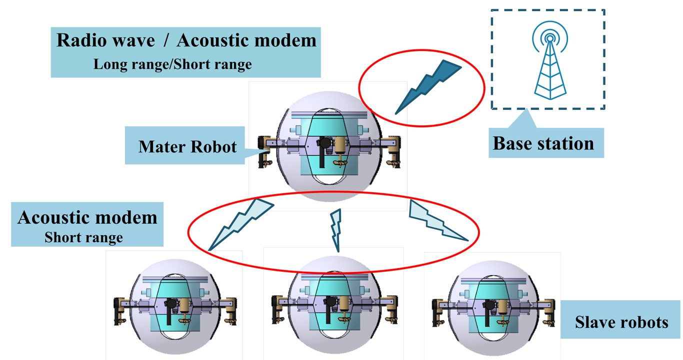


Fig. 2. Multilevel communication systems between a base station and multi-SURs.

II. SUR IV-Based Multilevel Underwater Acoustic Communication System

A. Prototype of SUR IV

The SUR IV is a spherical underwater robot that has the advantages of zero turning radius, good flexibility and so on. Fig. 1 is an exploded view of SURIV. The SUR IV consists of two hemispherical shells, a waterproof compartment that includes and protects the entire control unit, and a hybrid propulsion system with four hybrid thruster units. The diameter of the spherical hell is 45 cm, fours thrusters are evenly distributed at 90 °at the equator of the sphere, allowing the robot to achieve zero turning radius rotation, so that the robot can move at will in a space with a diameter. In the control system, the acoustic modem needs to be exposed to the water, so as to be placed on the outside of the bottom of the waterproof bin. The SUR IV possesses advantages of good efficiency, multipropulsion mode and multi-DoF. However, the ability of a single ball is still limited.

B. Multilevel Communication Systems for SUR IV

Fig. 2 illustrates the multilevel communication system for the SUR IV. In this system, the first level is the base station, the second level is the master robot and the last is the slave

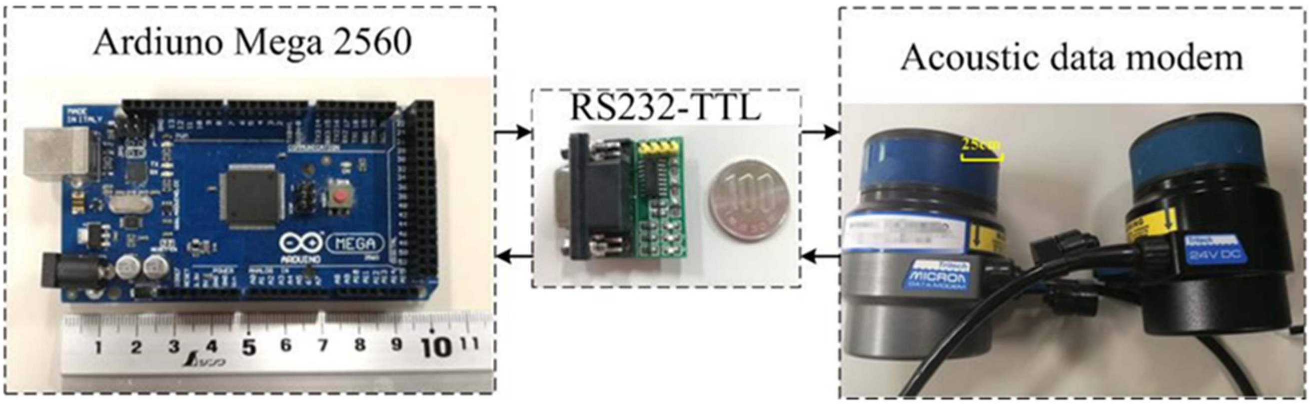


Fig. 3. Hardware of the UWAC system.

TABLE I
SPECIFICATION OF THE MICRON DATA MODEM

Specification	Parameter
Frequency band	20–28 kHz
Data rate	40bit/s (spread spectrum)
Range	500 m horizontal, 150 m vertical
Weight in air	235 g
Weight underwater	80 g
Depth rating	750 m

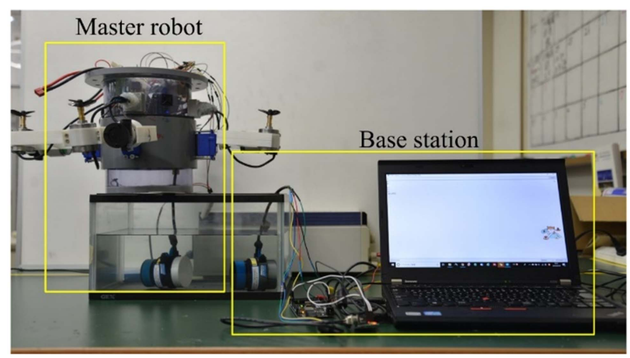


Fig. 4. Experimental setup for single-character instruction.

robots. The master robot will communicate with the base station by using radio waves for long-range (more than 450 m in horizontal and more than 120 m in vertical) and an acoustic modem for short-range. The master robot is more like a buoy that can be floated and moved on the water. The slave robots will communicate with the master robot by using an acoustic transmission.

To implement the above multi-level communication system, an UWAC system for both the base station and SUR IV is established. Fig. 3 shows the components of the UWAC system for a single robot or base station, including the Arduino Mega2560 development board, as the centralized control, one Micron data modem and an RS232 and TTL signal conversion board. The Micron data modem is a product from Tritech International Ltd. It can provide a means of robust spread spectrum data transmission acoustically through CHIRP signal in the water. Details of this modem are given in Table I. The frequency will be increased up to the maximum of 28 kHz or decreased down to 20 kHz with time as the CHIRP signal. The modem also has the tolerance of the Doppler effect at the range of ± 5 m/s.

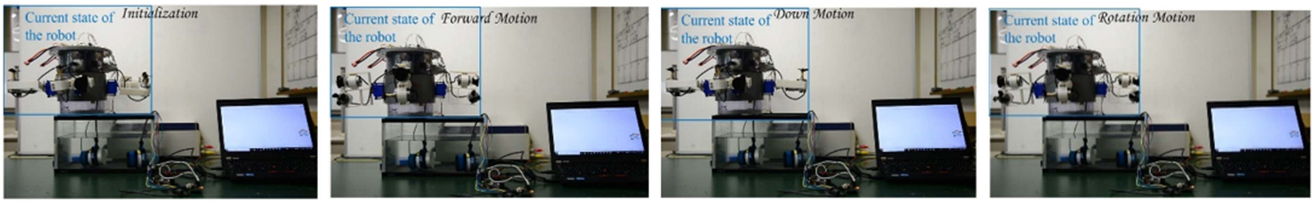
The Micron data modem just has the RS232 serial port and its logic "1" is from -3 v to -15 v as well as logic "0" is from 3 v to 15 v. The conversion board with an RS232 and TTL conversed chip is employed to debug with the modem. The baud rate is 9600 in this system. The modem can be put directly underwater. But the connector of the module is not wet and direct exposure to water when the unit is powered will cause damage. Therefore, we made a hole under the waterproof bin of SUR IV for wiring and placed the communication module on the outside of the bottom of the waterproof bin as shown in Fig. 1 to ensure that the communication module can always be in the horizontal plane of the water.

C. Communication Accuracy Experiments

To verify the ability of multi-level communication accuracy between base station and SURs, some experiments in different cases were conducted as the supports of this part. Experiments include two cases as following,

1) Case 1: Verification of Single-Character Instruction for Fast Communications: Although the communication in our research is based on multicharacter instructions, fast communication as single-character instructions cannot be ignored. In case 1, the purpose of this experiment is to verify the accuracy and response time of single-character instruction, so the base station will send a series of single-character motion instructions as initialization, forward motion, rotation motion and diving motion to the master robot. The experimental setup is shown in Fig. 4.

Fig. 5 illustrated the response time and accuracy of motion switches of the master robot after entering different single-character-instruction at the base station. The current instruction



(a) (b) (c) (d)

Fig. 5. Instructions input and motion execution of SUR IV. (a) Initialization. (b) Complete forward motion after entering the instruction. (c) Complete diving motion after entering the instruction. (d) Complete rotation motion after entering the instruction.

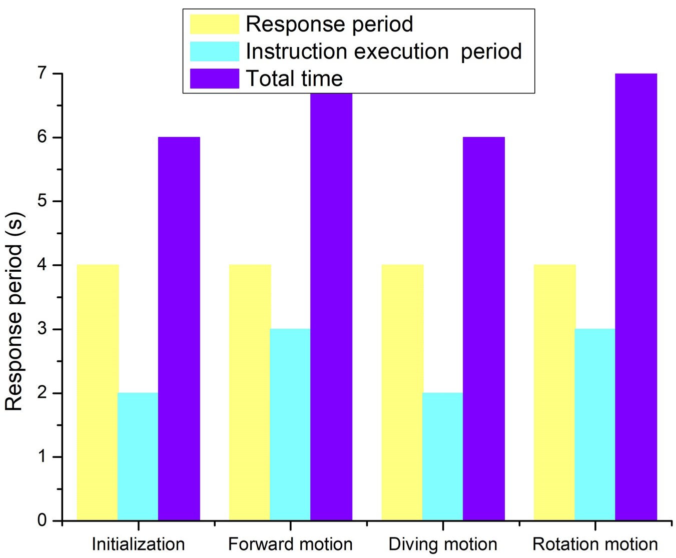


Fig. 6. Response and execution period.

set includes four different common motions, namely initialization, forward motion, diving motion and rotation motion. The whole experiment is carried out continuously, and the instruction input sequence is shown in Fig. 5(a) to (d). Since all instructions are a single character, the time of each instruction input is the start, until SUR IV gives a response, it is recorded as the response time, and the rest until the motion is completed is recorded as the instruction execution period. The response time of the completion command is 6–7 s, which are the results obtained after completing the four motion instructions in the experiment. In the response time, 4 s is the time to transmit and receive instructions, and 2–3 s is the time when servo motors or dc motor performs the action after the robot receives the instructions. For all single-after entering the instruction after entering the instruction after entering the instruction character instructions, the robot can execute accurately in experiments. The details of the response time are referred in Fig. 6. There are two items to be discussed with the response time in one transmission circle. The first item is the response period which starts with the instruction input to the PC and ends with the robot beginning to execute the instruction. The second item is the period when the robot performs the action after receiving the instruction. The execution period includes the time when the servo and the motor complete all the specified actions. Observing the change of response and execution time under different instructions, the response time is that the instruction receiving time is fixed, both are 4 s. The execution time will vary slightly depending on the actual situation, between 2–3 s, but the gap is not very large. The total time gap is also the gap in execution time.

2) Case 2: Stationary Object Detection: The other experiment on communication accuracy and execution effectiveness is case 2 as the detection of the stationary object. Fig. 7(a) is the experimental site of the stationary object detection. The obstacle consists of two rubber ball buoys with a diameter of 59 mm, and a 2 kg counterweight falls below to ensure the position remains unchanged. The distance between the front of the robot and the detection object is 1 m, and the base station is in the lower right corner in Fig. 7(a). The progress of the object detection for SUR IV is illustrated from Fig. 7(a) to (h). The base station issues an instruction at 0 s in Fig. 7(a), the robot receives the instruction after 4 s and acts accordingly as shown in Fig. 7(c). From 4 to 12 s, the SUR IV is approaching the object according to the instruction. In fact, in the eighth second, the base station has issued a stop instruction according to the distance between the current robot and the target, and the robot executes the stop instruction in 12the seconds with a slight brake inertia action as shown in Fig. 7(g) and (h).

The relationships between the velocity and time, distance and time are shown in Fig. 8. The red line indicates the velocity of the robot and the blue line is the displacement of the robot. According to the velocity curve, the robot has an acceleration behavior after receiving the instruction for the first time at 4 s, and after the second instruction is received at 10 s, there is a significant deceleration braking behavior.

III. Cooperation Between Base Station and SURs

A. Communication Principles

In previous studies, the accuracy, effectiveness, and timeliness of communication systems can be determined by experiments in Section II. In the following study, in order to cope with cooperation between multi-level communication systems, an instruction set for multicapacity and multilevel communication must be established. The establishment of the multicapacity can realize communication without interference between multi-SURs, and the instruction set also can reduce communication frequency and response time.

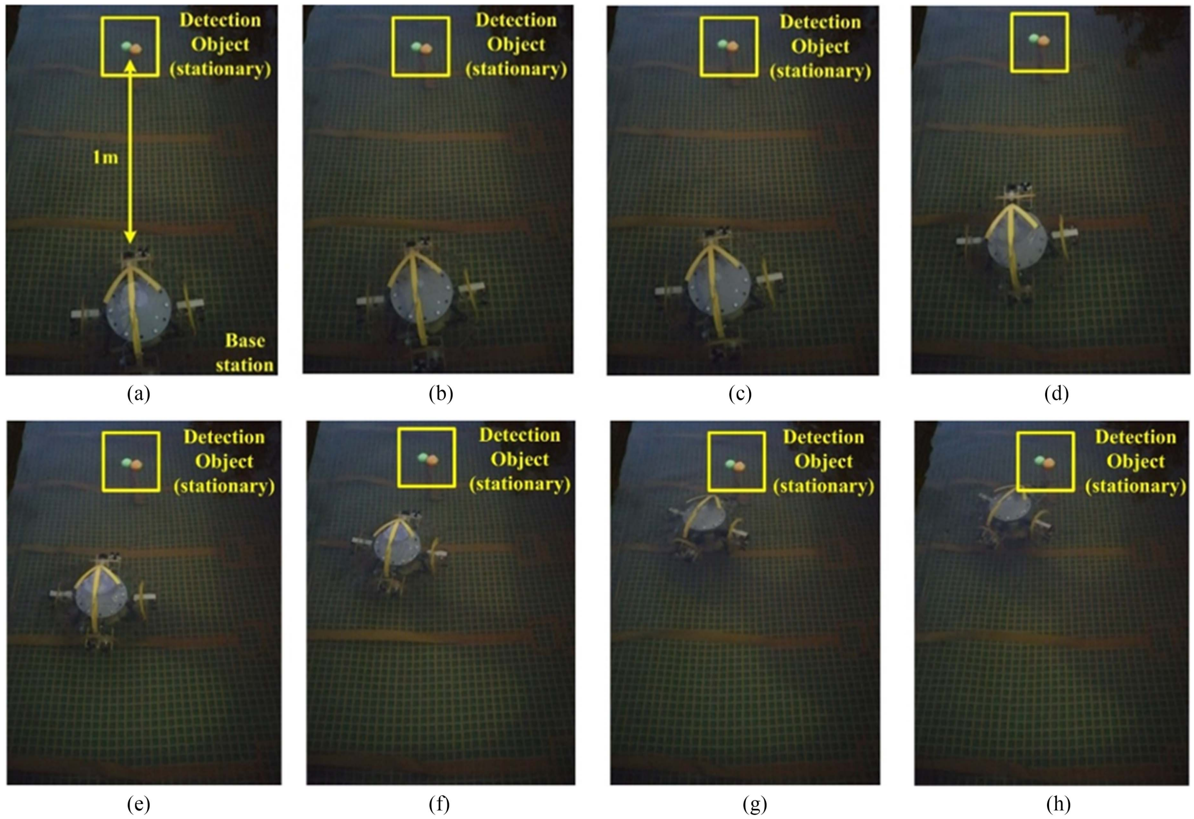


Fig. 7. Experimental site and progress for stationary object detection. (a) at 0s. (b) at 2s. (c) at 4s. (d) at 6s. (e) at 8. (f) at 10s. (g) at 12s. (h) at 14s.

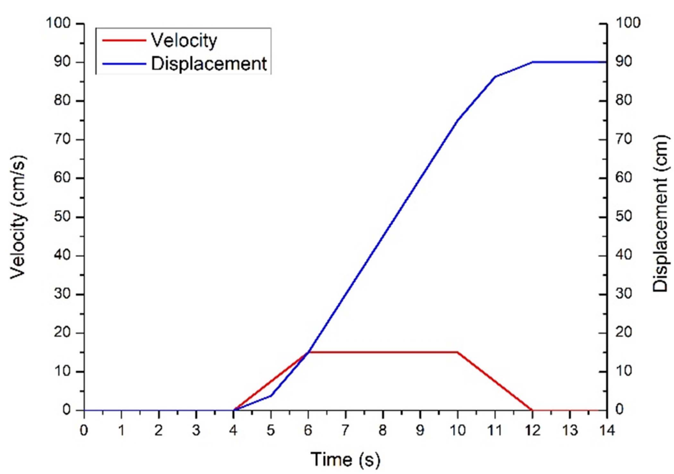


Fig. 8. Velocity and distance of the robot for stationary object detection.

The communication and cooperation motion between multi-SURs are important and very difficult, and it is necessary to cooperate with the localization system and the communication system. Fig. 9 shows the block diagram of the communication and cooperation motion between the master robot and slave robots. There are three communication principles for the multilevel cooperation motion as follows, these

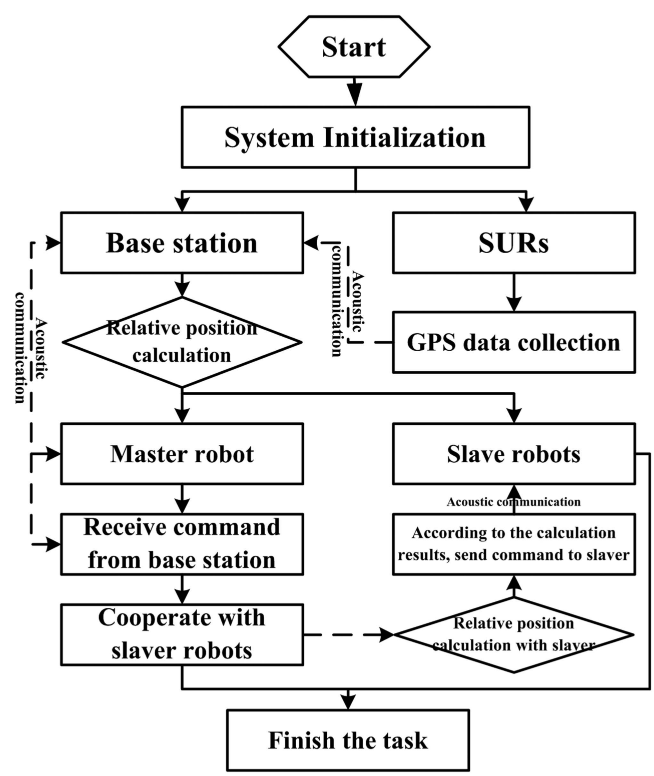


Fig. 9. Block diagram of the cooperation motion.

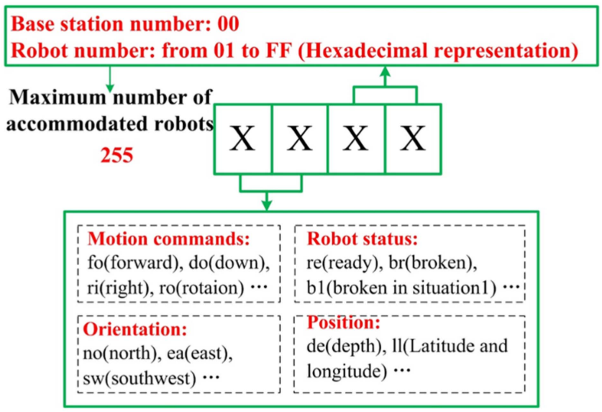


Fig. 10. Guidance of the conventional instruction.

principles prevent communication interference between differ-ent

levels.

Communication principles are as follows.

1) The base station can only communicate with the master robot once the master robot is selected.
2) The slave robots can only communicate with the master robot after the master robot is selected.
3) If the master robot is broken, the base station will choose a slave robot that is closest to the base station as the new master robot.

What needs to be explained here is that under normal circumstances, the base station can establish a communication relationship with each robot, but in order to reduce unnecessary losses and improve the efficiency of wages, when the master and slave robots are determined, the communication should be following the above principles. The above three principles are the basis of multi-SURs communication and cooperation, and it needs to be kept in the communication process. In the block diagram described in Fig. 9, it is premeditated that the number of slave robots is not one, and the establishment of multicapacity communication is a problem to be considered next.

B. Establishment of Multicapacity Communication and Instruction Set

The instruction set is used as the basis for implementing multicapacity communication. As given in Table I, the data rate of the acoustic modem is 40 bit/s. After our tests, the acoustic communication module can transfer up to four characters at a time, which means that when the transmitted command exceeds four characters; the number of communications will increase to twice or more. According to the above feature of the underwater acoustic module, we have established an instruction set that includes four characters and four characters or less. The allows valid instructions to be completed under one transfer.

In line with the number of characters and functions, the instruction set is also divided into three types as conventional instructions, unconventional instructions and reduced instructions. The guidance of the conventional instruction is described in Fig. 10. A four-character instruction consists of Arabic numerals and Alphabet to describe the robot status and simultaneous multicapacity of the robot. The first two characters of a conventional instruction represent the robot's status as motion commands, ability to work, orientation and position collection. The last two characters of the conventional instruction are expressed in hexadecimal to represent the number of the robot. The base station is set as the number 00 in this research. The robot number is from 01 to FF with the maximum number of accommodated robots as 255.

The unconventional instruction is the four-character instructions in addition to conventional instructions. The latter two characters in this instruction, which is particularly required to be specifically described here, is the sequence number that no longer represents the serial number of the robot in the communication system. This four-character instruction is mainly aimed at the unified action or information collection of all the robots in the system. The reduced instruction consists of three-character, two-character, and one-character instructions which for the entire communication system and describes some quick instructions. The reduction in characters allows the base station to quickly output these instructions and quickly pass information.

C. Experiments and Results

For verification of the effectiveness of the communication and cooperation for the multilevel model based on a base station, master robot and slave robots, some experiments were presented in the pool. The scale of the pool is the same with the one in Section II. There are also two cases in this part, namely, the master-slave robot following and the position tracking experiments, and the master-slave robot follows for the obstacle avoidance experiment.

1) Case 1: Master-Slave Robot Following and the Position Tracking Experiments: In this experiment, the base station only sends an instruction to the master robot and the master robot will only send an instruction to the slave robot as the communication principles. Fig. 11(a) shows not only the experimental site but also the initial state of the experiment. The progress of the experiment is illustrated from Fig. 11(a) to (f). The master robot receives the forward command from the base station. Considering the transmission time and to prevent collisions, the master robot will send the following command to the slave robot after executing the motion instruction. The slave robot follows the master robot at the seventh second. During the following process, the base station finds that the direction of the slave robot is offset from that of the master robot, which is the base station that will prompt the master robot in this experiment. The master robot sends another instruction to the slave robot to adjust the offset, so the slave robot turns left at the 15th second. Finally, the slave robot is tracked to the position of the master robot at the 20th second.

The trajectories of the master robot and slave robot are shown in Fig. 12. The red line is the motion trajectory of the master robot, and the black line indicates the motion trajectory of the slave robot. Although the short offset of the following path is caused by the deviation of the slave robot due to the initial

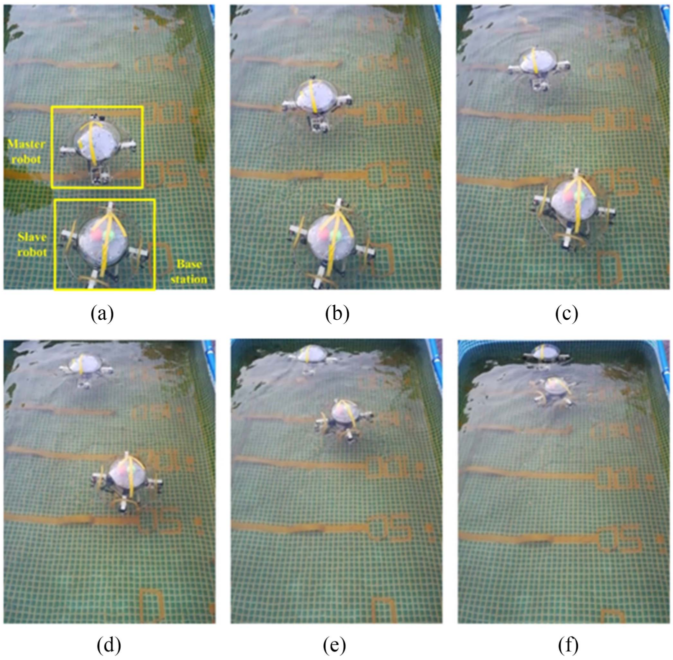


Fig. 11. Progress of master-slave robot following and the position tracking. (a) at 0s. (b) at 4s. (c) at 8s. (d) at 12s. (e) at 16s. (f) at 20s.

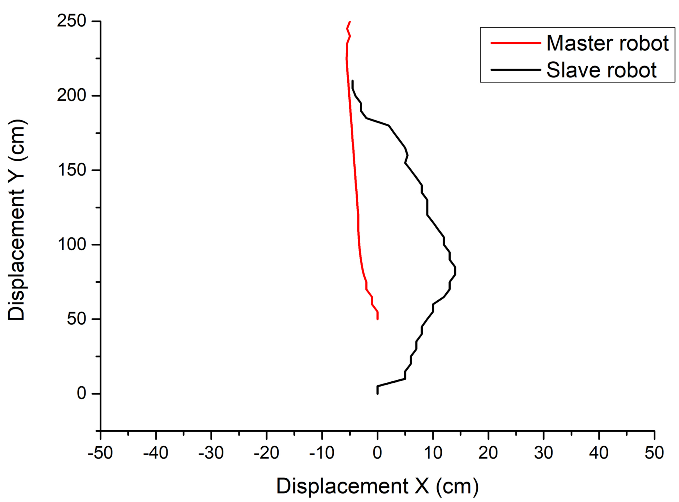


Fig. 12. Trajectory of the master robot (red) and slave robot (black).

position angle, after the correction instruction from the master robot, the correct track is returned.

2) Case 2: Master-Slave Robot Following and Obstacle Avoidance Experiments: Since the entire experimental site is not fully summarized in the experimental diagram, the experimental site and experimental planning are introduced using Fig. 13. An obstacle is set at the left side of the pool, the obstacle consists of two rubber ball buoys with a diameter of 59 mm, and a 2 kg counterweight falls below to ensure the position remains unchanged. The distance between the obstacle and the master robot is 1.5 m. The master robot will lead the slave robot to avoid the obstacle through the designed trajectory in Fig. 13. The progress of this experiment is described from Fig. 14(a) to (h). At first, the base station transmits the forward instruction

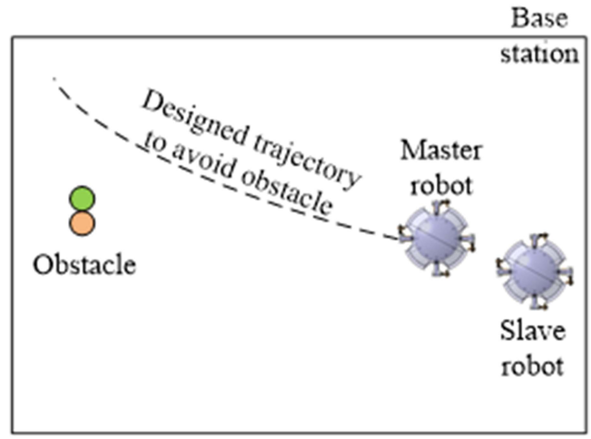


Fig. 13. Experimental setup for obstacle avoidance.

to the master robot, and the slave robot receives the following instruction from the master robot. The base station finds the obstacle and informs the master robot to avoid the direction and angle of the obstacle, and the master robot thus guides the slave robot to avoid the obstacle together. At the 16th second, the master robot has successfully avoided obstacles under the guidance of the base station. At the 19th second, we can observe the path from the end robot to follow the main robot to avoid obstacles. At the 21st second, the slave robot successfully evades the obstacle and continues to follow the motion.

The trajectories of the master and slave robots are illustrated in Fig. 15. The red line shows the track of the master robot and the black line indicates the slave robot. In fact, the slave robot first receives the following instruction. After the master robot receives the alert from the base station about the obstacle position. The master robot first plans its path and then sends the following obstacle avoidance instruction to the slave robot.

IV. Discussion

Communication and cooperation are very practical for complex underwater researches and explorations. Monolithic robots, especially miniaturized robots, have limited capabilities, but when swarm robots can effectively cooperate with each other, the situation tends to be improved. Therefore, it is necessary to study how to make swarm robots work effectively and correctly.

In this article, a novel underwater wireless communication system by using acoustic modems was proposed. On this basis, the cooperation between a base station and multi-SURs was realized by the establishment of the multicapacity. The accuracy and timeliness of signal transmission and reception were critical for underwater communication systems. Therefore, this article used a series of experiments to verify the validity and corresponding time of transmission and reception including conventional instructions and reduced instructions. In addition, a multilevel cooperation model was established based on a base station, master robot and slave robots. The feasibility of the model was verified by experiments.

Despite the promising results, it is important to notice that the study is limited by the scale of the pool. Although the pool

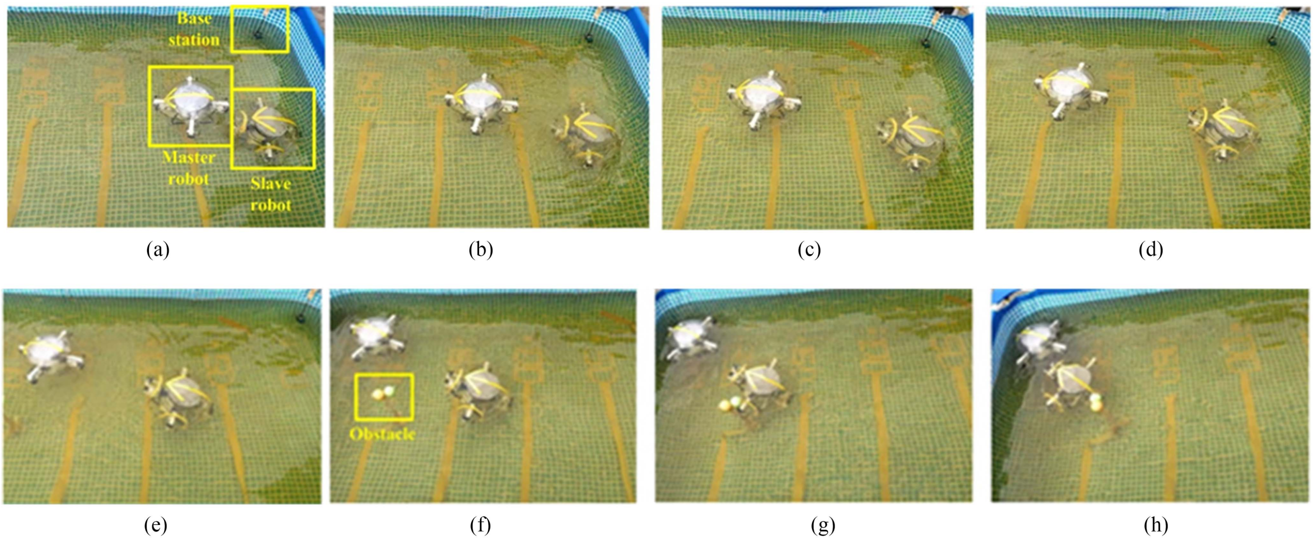


Fig. 14. Progress of master-slave robot following and obstacle avoidance. (a) at 0s. (b) at 4s. (c) at 7s. (d) at 10s. (e) at 13s. (f) at 16s. (g) at 19s. (h) at 21s.

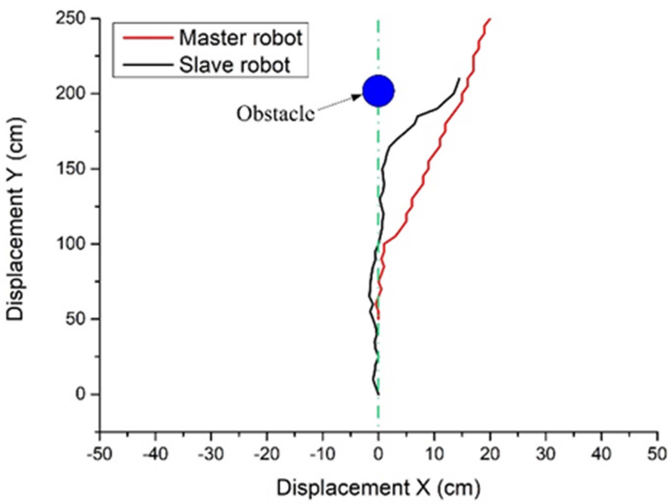


Fig. 15. Trajectories of the obstacle avoidance experiments.

is built outdoors, the small size does not completely mimic the open water environment. Limited by the size of the pool, only two SURs were used to act as the master and slave. However, the concepts of the communication and cooperation method presented in this article can confirm its usability and effectiveness in experiments. In the future, some open and larger waters will be chosen, and more SURs will be used to accomplish the more complex task.

V. Conclusion

In this article, the communication system was developed by using acoustic modems with the aid of a localization system for SUR IV. This is a relatively novel attempt for miniature robots (45 cm diameter), because in the past, acoustic communication was often used on large-scale robots since the size of the equipment. The experiments in Section II in the pool proved the accuracy, effectiveness and timeliness of the communication system. To realize the communication and cooperation between a base station and multi-SURs, the instruction set with multicapacity communication was established. The instruction set includes conventional, unconventional and reduced instructions. The maximum number of accommodated robots for multicapacity is 255 in this research. Finally, the communication and cooperation experiments show that the base station, master robot and slave robot can cooperate well with each other to finish some simple tasks.

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