Proceedings of 2023 IEEE
International Conference on Mechatronics and Automation
August 6 - 9, Harbin, Heilongjiang, China

Evaluation of Detection System for Bioinspired Spherical Underwater Robots Based on the Pressure Sensor Array

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***Abstract* – Due to the particularity and complexity of the underwater environment, the perception ability of Autonomous Underwater Vehicles (AUVs) has become a hot issue in recent years. In this paper, the detection system was developed for bioinspired Spherical Underwater Robots (SURs) based on the pressure sensor array. Firstly, the sensor array based on the SUR model was proposed using pressure sensors, adding new dimension to near-flow detection and perception method. Then, the detection system was constructed and the hydrodynamic pressure variables are analyzed. Next, the data acquisition of the pressure sensor array was described. Furthermore, the SUR prototype was assembled carrying the pressure sensor array. Finally, a series of locomotion experiments were performed to verify its performance. The experimental results validated the effectiveness of the proposed detection system, which had a certain reference value for AUV underwater detection and state estimation.**

Index Terms – Detection system, Pressure sensor array, Spherical underwater robot, Data acquisition, Locomotion.

I. INTRODUCTION

In recent years, AUVs have been widely used in marine resource exploration, dam maintenance, underwater rescue, etc. In order to enhance the perception of autonomous underwater vehicles in unknown environments, AUVs equipped with sensing systems can provide us with detailed flow information and obstacle information [1] - [3]. It has practical application value in autonomous obstacle avoidance and positioning of AUVs [4] - [5].

In addition, some sensor systems [6] - [7] have been developed, For instance, sonar is widely used for underwater detection, but there is a blind spot when working at close-range [8]. The camera system is easily affected by light in turbid underwater environments. Doppler analyzer can be applied to miniature underwater robots, but it has the disadvantages of being heavy and expensive [9] - [10]. Due to these limitations, detecting underwater targets and enabling AUVs to perform underwater tasks more accurately is an urgent problem to be solved. To improve the perception ability and task efficiency of AUVs, a series of perception systems inspired by the lateral line perception mechanism of fish have been studied [11] - [13].

As a kind of sensor system, the sensor array is more and more concerned by researchers to make AUVs avoid obstacles and reach the target more efficiently. AUV can accurately perceive the surrounding environment and enhance its adaptability to unknown environments using the sensor array [6], [14]. For example, *Liu et al.* [9], [15] proposed an artificial lateral line system for box fish to assist carrier movement and self-attitude perception. *Tang et al.* [16] designed a near-field detection system for a fish to add detection functionality to an underwater vehicle. *Sharif et al.* [11] fabricated a lateral-line differential pressure sensor and demonstrated its use in underwater applications through finite element simulation and feedback control experiments. *Liu et al.* designed a sensor system [17] to perceive the vibration source. *Guo* and *Li et al.* [6], [18] - [19] developed an ultrasonic sensor array for obstacle avoidance and path tracking. *Wang et al.* [20] achieved autonomous navigation using multiple sensors, which improved localization accuracy compared to traditional localization methods. These detection systems using sensor arrays, such as the artificial lateral line system and obstacle avoidance based on ultrasonic sensors provide new ideas for AUVs in underwater applications [21] - [22]. Although some sensor arrays have been proposed to perform obstacle avoidance and velocity estimation of AUVs, the near-field adaptive detection and underwater applications of AUVs are still insufficient. For micro bioinspired SUR, it is difficult to carry large-scale sensor equipment. Considering the complexity of the unknown underwater environment, it is urgent to develop a detection system for SURs. The pressure sensor array is an effective method to solve such problems.

Motivated by the above consideration, this paper, therefore, designs a novel near-field detection system for SUR based on the pressure sensor array. The detection system consists of six pressure sensors, which are arranged on the body surface of the SUR. The detection system can collect pressure information from all directions. In contrast, SUR equipped with a detection system can accurately detect information such as adjacent walls and obstacles, and has less impact on the marine biological environment. The SUR with detection system and its application scenarios are shown in Fig. 1.

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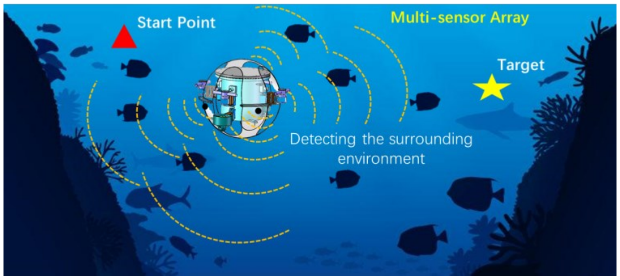

Fig. 1 The application scenes of SUR with the detection system.

This paper is organized as follows: The prototype of the SUR, the features of the pressure sensor and the proposed pressure sensor array are introduced in Section II. Then, in Section III, a detection system is proposed for SUR to achieve data acquisition and underwater detection. The main work of Section IV carries out locomotion experiments. Next, we analyze the performance of the proposed detection system. Finally, Section V introduces conclusions and future work.

II. Prototype of Bioinspired SUR Design

A. *Previous research of the SUR*

In our previous research, a SUR inspired by the propulsion mechanism of jellyfish is developed [23] - [24]. As we know, natural jellyfish is a beautiful creature with a body shaped like a transparent umbrella. By shrinking the shell to change the volume of the inner cavity, the water in the cavity is sprayed out, which will form areas of different pressure levels around the body. The jellyfish then swim in the opposite direction. Therefore, to imitate the advantages of jellyfish motion in terms of symmetry and stability, a SUR with a hybrid thruster is developed, consisting of the propeller thruster and water-jet thruster. The SUR with hybrid propulsion can approach the target stably, quickly and efficiently, and complete the mission successfully.

TABLE I
Specific parameters of the SUR

Items	Characteristics
Diameters	Hemispheres 540 mm; Control cabin 140 mm
Total Mass	Approx. 7.9 kg
Drive Mode	Multi-mode (water-jet mode, propeller mode and hybrid mode)
Onboard Controller	Arduino Mega 2560, Steering gear controller (ARM Cortex-M3), ACEIRMC 5pcs L298N and ESC
Power Supply	12V Rechargeable Batteries
Communication Module	Micron Data Modem (Tritech)

The SUR we designed has the characteristics of small-size, low-noise and flexible-motion. In [25], the structure is designed and basic motion is analyzed. And we analyzed the hydrodynamic characteristics of the hybrid thruster in [24]. In addition, some control strategies, such as attitude regulation, multi-mode adaptive switching control and trajectory tracking control are developed based on the kinematic and dynamic models of the SUR in [1], [6], [26] - [27]. Furthermore, the performance of some sensors is evaluated in [18], such as the application of the communication module in multi-robot collaboration, the application of the ultrasonic sensor in obstacle avoidance strategy, etc.

Table I reveals the specific parameters of the SUR with hybrid thruster. The dimension and the control cabin of the SUR are 540 mm and 140 mm, respectively. The total mass of the SUR in air is 7.9 kg. The SUR carries the sensors, e.g. Inertial Measurement Unit (IMU), the acoustic communication modem to adjust attitude and transfer information in real-time.

B. *The pressure sensor CJMCU-5837*

CJMCU-5837 pressure sensor adopts MS5837-30BA, which is a high-resolution pressure sensor with I2C interface. Its small size of 10 mm x 18 mm makes it easy to install, as shown in Fig. 2. The waterproof performance is guaranteed by gel and an anti-magnetic stainless steel cap. MS5837-30BA provides precise 24-bit digital pressure, temperature value and different operation modes. The specification of the pressure sensor is shown in Table II.

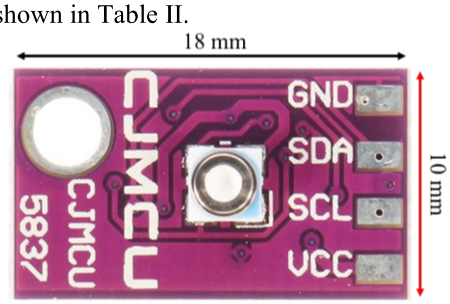

Fig. 2 The pressure sensor of CJMCU-5837.

TABLE II
Specification of the pressure sensor CJMCU-5837

Items	Specifications
Brand	CJMCU
Pressure sensor type	MS5837-30BA
Size	10 mm x 18 mm
Analog to digital converter	24 bit
Working voltage	3 – 5 V
High-resolution	0.2 mbar
Communication	Inter-Integrated Circuit BUS (I2C)
Operating range	0 - 30 bar, -20 to +85 °C

Its communication protocol is simple, allowing users to configure conversion speed and power consumption according to actual needs. Furthermore, the function of a thermometer can be implemented without additional sensors.

C. *Proposed pressure sensor array*

For bioinspired AUVs, such as fish, perceives and respond to the external environment mainly through the superficial neuromast. When its body is hit by the water flow, the pressure of the water enters the tube through a series of pores in the sideline tube. Thus, the obtained external stimulation is transmitted to the nerve center through nerve fibers, and a series of behaviors are made. Many researchers have used such sensor array systems to provide new perspectives for AUVs in the field of underwater environment sensing. In this paper, the pressure sensor array for the SUR is proposed, as shown in Fig. 3. Compared with a single sensor, the sensor array adds a new dimension to AUV observation, helping to estimate more parameters and improve estimation performance. Sensor arrays are typically deployed in patterns such as the linear array [28], circular array [6], planar array, and spherical array.

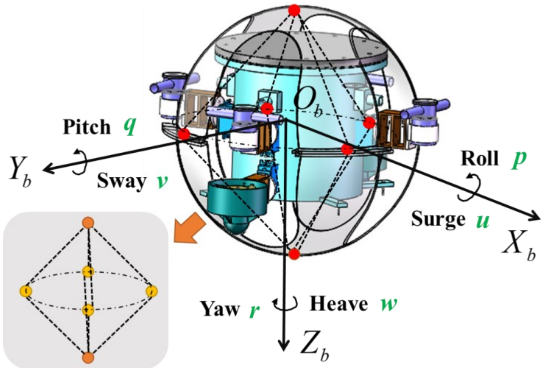

Fig. 3 The SUR-fixed coordinate frame and stereoscopic model of the proposed pressure sensor array.

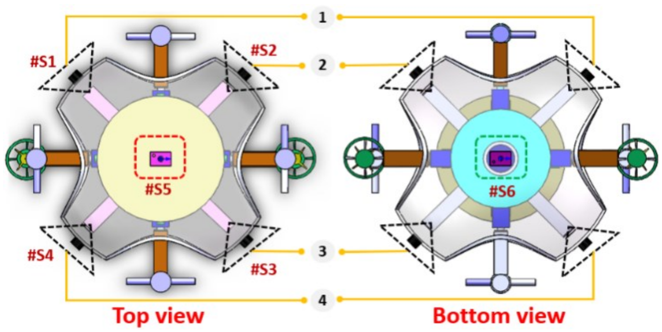

Fig. 4 The proposed sensor array for SUR using pressure sensors.

In [23], [29] - [30], we analyzed the hydrodynamic properties of SUR. The surrounding fluid domain is investigated as the SUR moves. We found from the pressure contour diagram that the pressure on the robot's locomotion direction is the most obvious, which is also the most reasonable position to capture the pressure characteristics of the surrounding environment. Hence, considering the motion characteristics and high symmetry of the SUR, and better perception of the surrounding fluid flow, a total of six pressure sensors are used to design the sensor array. The pressure sensor array layout for the SUR is shown in Fig. 4. The sensor array is distributed symmetrically in the center, and the pressure sensor (*#S5*) is installed at the top, the pressure sensor (*#S6*) is installed at the bottom, the remaining four pressure sensors are installed in the center circle. Noted that the pressure sensors (*#S1* to *#S4*) are distributed clockwise with respect to the traveling direction.

The pressure sensor module is sealed with silicone after the DuPont lines are led out, and fixed on the SUR body with the screw to ensure that the module will not shake when it is impacted by water waves. The power supply unit and the microcontroller unit are connected to the pressure sensors in the control cabin.

III. Design of the Detection System

In this section, the detection system using the pressure sensor array is designed for SUR to provide a guarantee for performing underwater tasks. Firstly, the hydrodynamic pressure variables are analyzed. Then, a data acquisition scheme for the pressure sensor array is proposed. Finally, the detection system was constructed for the SUR.

A. Analysis of hydrodynamic pressure variable

As mentioned in [11], [31], the linear equation of the pressure difference *p* of the SUR surface with respect to the actual pressure and the hydrostatic pressure can be expressed as:

$$p = -\rho \frac{\partial \Phi}{\partial t} - \rho g y \tag{1}$$

where *p* is the pressure difference between actual pressure and hydrostatic pressure, ρ, g, y represent the water density, gravitational acceleration and dive depth, respectively.

Fig. 5 is the hydrodynamic pressure variable on the surface of the SUR, and the displacement from equilibrium is indicated by $X = A \cdot w \cdot \sin(wt)$. The position of the target source is indicated by (x_t, y_t) , and the position of the sensor is indicated by $(x_i, y_i), i = 1\ldots6$. r_i is the distance between the sensor and the target source, satisfying: $r = \sqrt{(x_t - x_i)^2 + (y_t - y_i)^2}$. θ is the angle between the variable axis and *r*.

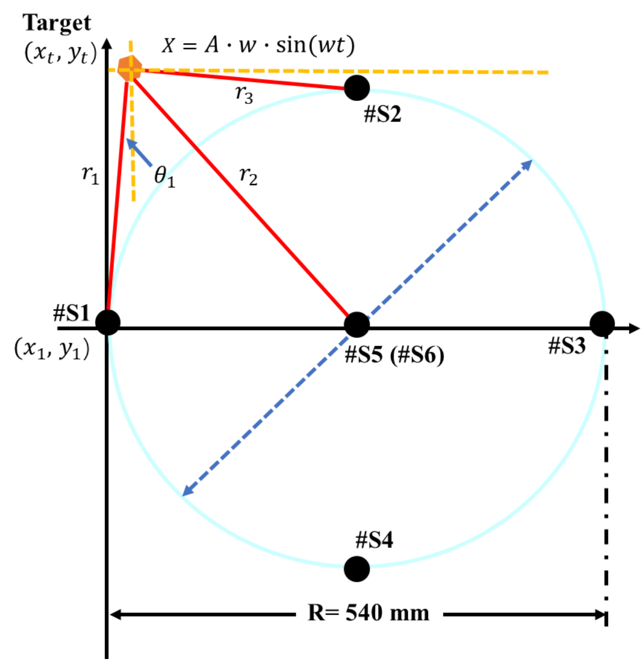

Fig. 5 The hydrodynamic pressure variable on the surface of the SUR.

Here, the potential function can be derived using the approximate Laplace equation:

$$\Phi = -\frac{R^3}{2r^2} X \cos\theta \tag{2}$$

where R denotes the radius of the vibration resource; $\cos\theta = (y_t - y_i)/r$.

Substituting the parameters into Equation (2), yields:

$$\Phi = -\frac{R^3 A \cdot w \cdot \sin(wt)(y_t - y_i)}{2\left[(x_t - x_i)^2 + (y_t - y_i)^2\right]^{\frac{3}{2}}} \tag{3}$$

Thus, the pressure calculation of the near-field generated by the target source can be expressed as:

$$p = -\frac{\rho R^3 A \cdot w \cdot \cos(wt)(y_t - y_i)}{2\left[(x_t - x_i)^2 + (y_t - y_i)^2\right]^{\frac{3}{2}}} \tag{4}$$

B. *Proposed detection system*

In this paper, the prototype of the SUR adopts a symmetrical and spherical body. The driving unit is consisted of the steering gear (HS-5646WP, 41.8 mm x 21.0 mm x 40.0 mm, IP67) and the hybrid propulsion devices for improved adaptability and maneuverability. The data transmission is achieved by micro sonar (Acoustic Communication, Tritech). Three micro Li-polymer (ACE, 2200 mAh) batteries provide more than three hours of battery time. The Arduino micro-controller is selected, whose device core is ARM Cortex M3, it has rich resources. The micro-controller communicates with the pressure sensor using I2C, as shown in Fig. 6.

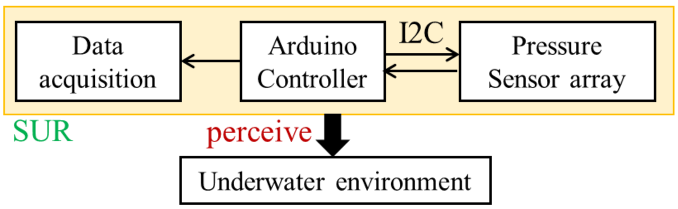

Fig. 6 The proposed detection system for SUR using pressure sensor array.

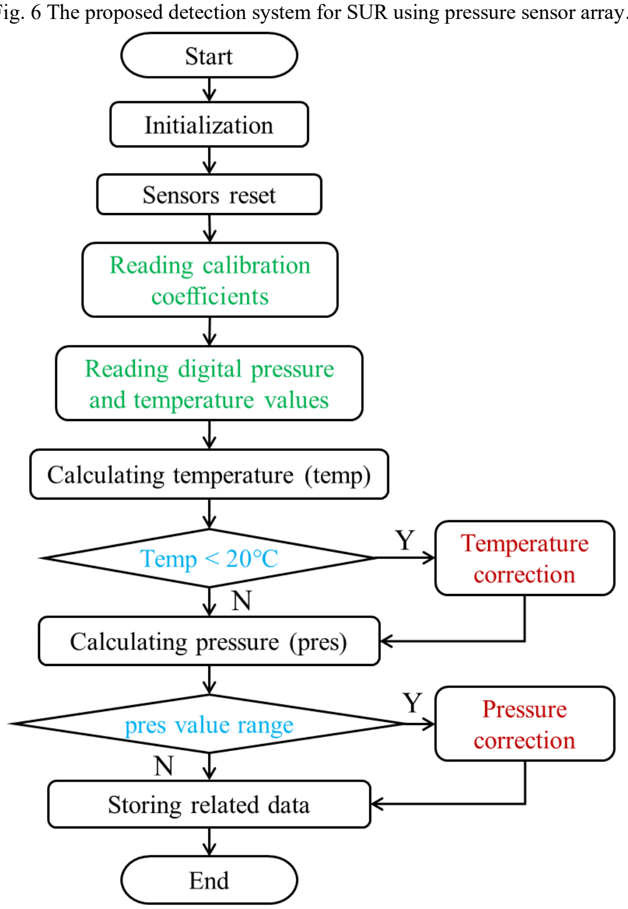

Fig. 7 The process of pressure data acquisition.

The process of pressure data acquisition is shown in Fig. 7. After the SUR perceives the external environment, the pressure sensor communicates with the controller through I2C, and analyzes the pressure difference by analyzing the transmitted data.

IV. Experimental Results and Discussion

In the experiments, the SUR prototype is assembled and a

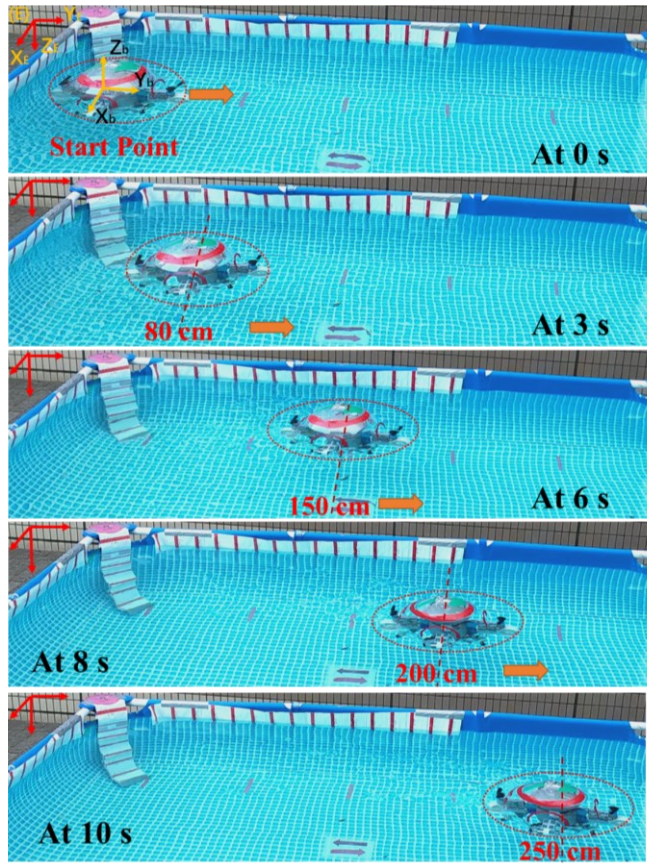

Fig. 8 The locomotion process of the SUR.

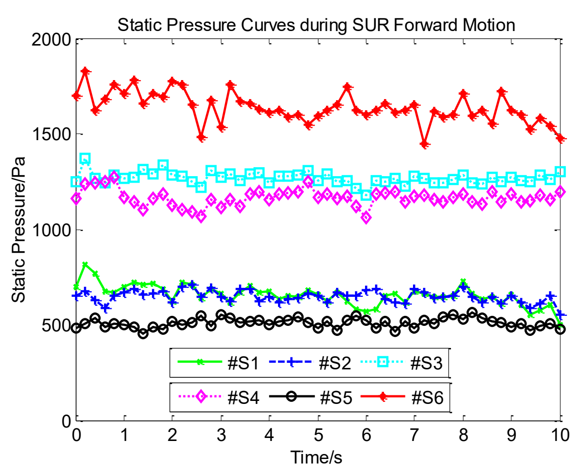

Fig. 9 Results of pressure measurement during locomotion.

series of locomotion experiments were carried out in a pool with the size (length 300 cm x width 200 cm x height 100 cm). The experimental environment temperature is about 25 °C. In the locomotion experiments, a total of five experiments were performed.

In the forward motion, the SUR traveled in a straight path at a fixed velocity of 0.22 m/s, and a distance about 2.5 m. Fig. 8 showed the motion process of the SUR. The measured result recorded by the pressure sensor array during forward locomotion were shown in Fig. 9. It could be seen that when the SUR moved in a straight line, the trend of the data was consistent, which was approximately constant. The reason may be that the dynamic component generated by the sensory pressure in uniform linear motion can be ignored.

Here, the time and frequency plots of hydrostatic pressure raw data were analyzed. Fig. 10 shows the raw data of pressure sensor *#S5*, including the original pressure signal, frequency domain distribution of pressure signal and filtered pressure signal. When the frequency is 0, as shown in Fig. 10 (b), a higher spike occurs due to the effect of Direct Current (DC) component. In order to better show the static nature of the original signal, it is necessary to filter out the dynamic component during the measurement to improve the measurement accuracy, as shown in Fig. 10 (c).

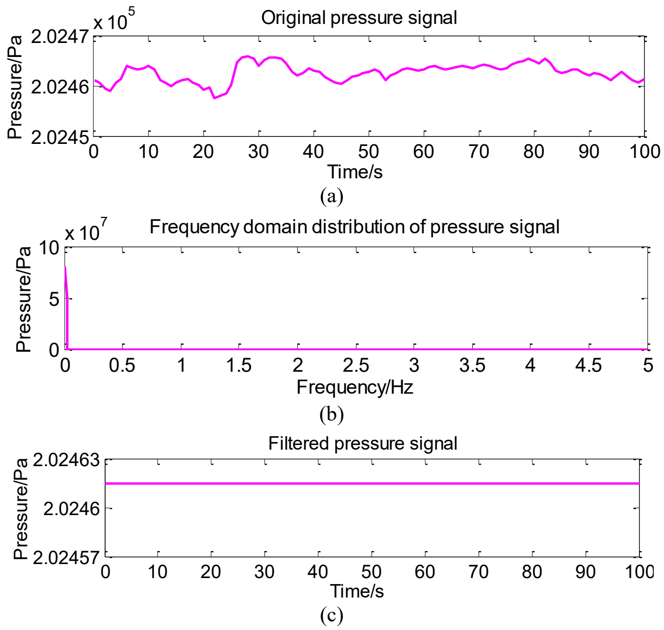

Fig. 10. The signal processing of the sensor *#S5* pressure data, including: (a) original pressure signal, (b) frequency domain distribution of pressure signal, (c) filtered pressure signal.

V. Conclusions

In order to improve the perception ability of SUR in the near-flow field and adapt to the unknown and complex underwater environment. A detection system based on pressure sensors was proposed. According to the pressure sensor characteristics and SUR hydrodynamic model, the pressure sensor array is constructed. In the detection system, the hydrodynamic pressure variable was analyzed to improve the performance of the pressure sensor array. Then, the data acquisition of the detection system by the Arduino micro-controller was analyzed. Finally, a series of locomotion experiments were performed to verify the effectiveness of the proposed detection system. The experimental results validated that the detection system of the SUR could accurately perceive the near-flow underwater environment. In the future, we will use the proposed detection system to complete SUR velocity and attitude estimations to improve the application value of SUR in unknown and complex environments.

Acknowledgment

This research is supported in part by the Japan Society for the Promotion of Science (SPS) KAKENHI under Grant 15K2120, and in part by the China Scholarship Council (CSC) for his doctoral research at Kagawa University under Grant 202208050040.

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