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Design and Implementation of a Robotic Dolphin for Water Quality Monitoring

Jincun Liu, Zhengxing Wu, and Junzhi Yu

Abstract— **This paper presents a novel mechanical design and multimodal locomotion control of a bio-inspired robotic dolphin for water quality monitoring. In order to obtain a better hydrodynamic performance, a robotic dolphin modelled after killer whale is developed. Depending on its powerful propulsive posterior body and fluke, the robotic dolphin can realize fast and flexible dolphin-like swimming. Moreover, a pair of pectoral fins with separate degree of freedom and a yawing dorsal fin are designed for turning maneuvers. Besides, many onboard sensors including an inertial navigation system, GPS, a depth sensor, infrared sensors and a replaceable water quality multiprobe are employed to implement autonomous water monitoring task. As for the control level, a Central Pattern Generators (CPGs) -based controller is utilized to realize multimodal locomotion including forward swimming, turning, diving and surfacing. Finally, both extensive experiments and field testing demonstrate the feasibility of the proposed bio-inspired water quality monitoring system.**

Index Terms— **Robotic dolphin, motion control, CPGs, water quality monitoring.**

I. INTRODUCTION

Recently, with the development of social economy and industry, water is readily polluted by the human activities such as toxic chemicals and untreated sewage. Water pollution has aggravated water resource crisis and threatened the health of human beings. Thus, some effective and practical equipments are urgently needed to monitor the water quality. The conventional way is to manually collect water samples and bring back to laboratories for analysis. This approach has so many disadvantages like complicated operation, long waiting time for results, low measurement precision, high cost, and uneasy to be implemented in large-scale, long-term, and on-line monitoring [1]. In addition, Autonomous Underwater Vehicles (AUVs) as monitoring platforms have been widely applied to oceanography and environmental monitoring [2]. But existing AUV itself is cumbersome so that a special vessel which has good facilities is needed to handle it like pulling up and down, which causes the expensive operational cost [3]. Besides this, there are also so many disadvantages such as low efficiency, poor maneuverability, and much disturbance to the environment.

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After a long periods of natural selection, aquatic animals, including fish and cetaceans, have evolved to become extraordinary morphological and structural features with remarkable speed, maneuverability, efficiency, and stealth [4]. As an excellent bio-inspired autonomous underwater vehicles, the dolphin-like or fish-like robots may be considered to apply to underwater environment monitoring. Compared with the propeller-based propulsion used in ship or underwater vehicles, the bio-inspired robots can be more suitable for underwater environmental monitoring in narrow, complex, and dynamic aquatic environment. In practice, there have been a lot of studies on bio-inspired robots in the context of water quality monitoring. Liang *et al.* designed a two-joint biorobotic AUV SPC-III, which had been successfully performed a 49 km probe experiment and collected concentration distributing data of blue-green algae in Taihu Lake [5]. Clark *et al.* proposed an evolutionary multiobjective optimization approach to the design and control of a robotic fish with a flexible caudal fin, which was applied to environmental monitoring, inspection of underwater structures, tracking of hazardous wastes and oil spills, and the study of live fish behaviors [6]. Shen *et al.* developed a water quality monitoring system based on a robotic dolphin, the system was composed of fixed monitoring nodes, robotic dolphin node and a console. By the coordination of the fixed measuring and dynamic measuring, the water quality parameters such as PH value, conductivity, dissolved oxygen and turbidity were acquired [7]. Ryuh *et al.* implemented a multi-agent robotic fish system used for collecting marine information such as water temperature and pollution level, each robotic fish was equipped with several onboard sensors for autonomous 3D navigation tasks such as path planning, obstacle avoidance, and depth maintenance in order to achieve intelligence and autonomy [8].

The aim of this paper, based on our previous research [9]–[12], is to design a novel mechanical design and multimodal locomotion control for a biomimetic robotic dolphin that is capable of water quality monitoring. A well streamlined shape like killer whale is chosen to improve the hydrodynamic performance. Moreover, compared with our previous work, a pair of pectoral fins with separate degree of freedom cooperate with a yawing dorsal fin in realizing turning maneuvers. Besides, the robotic dolphin is equipped with several onboard sensors, which allow it to be a self-propelled and self-contained system to implement autonomous water monitoring task. As for the control level, a Central Pattern Generators-based controller is utilized to realize smooth and stable dolphin-like swimming. Finally, in order to validate

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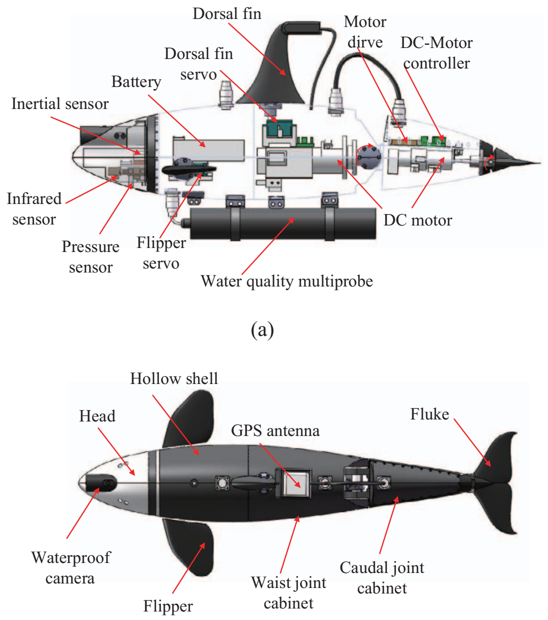

Fig. 1. Mechanical design of the robotic dolphin. (a) Side view. (b) Top view.

Fig. 2. Prototype of the robotic dolphin.

TABLE I
TECHNICAL PARAMETERS OF THE DEVELOPED ROBOTIC DOLPHIN

Items	Characteristics
Dimension ($L \times W \times H$)	$\sim 741 \times 132 \times 352$ mm^3
Total mass	~ 7.24 kg
Number of joints	5
Actuator mode	DC motors, Servomotor
Power supply	DC 24 V
Control mode	Wireless (RF)
Operation time	~ 3 h

the feasibility and the effectiveness of the proposed bio-inspired water quality monitoring system extensive aquatic experiments are conducted.

The remainder of this paper is organized as follows: Section II gives an overview of the developed robotic dolphin containing mechanical design and hardware architecture. The description about the adopted CPG network and implementation of multimodal locomotion are presented in Section III. Experiments of motion control and water quality monitoring are provided in Section IV. Finally, Section V summarizes the research progress and future work.

II. MECHANICAL DESIGN AND HARDWARE ARCHITECTURE OF THE ROBOTIC DOLPHIN

A. Mechanism Design

As illustrated in Fig. 1, we propose a mechanical design of a dolphin robot for water quality monitoring and the prototype is depicted in Fig. 2. The corresponding technical parameters of the developed robotic dolphin are tabulated in Table I. The robotic dolphin, which is inspired by killer whale, adopts spindle streamline structure for the purpose of reducing drag force to some extent. The shell is made of paraformaldehyde (POM) in order to enhance endurance capacity and reduce the weight. The robot is made up of five parts, i.e., a streamlined rigid head, a hollow shell, a waist joint cabinet, a caudal joint cabinet, and a water quality multiprobe. Among these parts are tightly screwed together via O-type sealing ring to improve the waterproof capability.
The rigid head consists of fiberglass and equips with a variety of onboard sensors. A pressure sensor is fixed on the low surface of the head offers depth data. Attitude and heading solution is offered by a inertial sensor, which is mounted in the head. The robotic dolphin assembles three infrared sensors that integrate with inertial sensor and pressure sensor to realize robotic autonomy. A waterproof camera, which is fastened to the front of the head to capture the environment information. Global Positioning System (GPS) is used for acquiring accurate three-dimensional position, velocity, and acceleration of the robot on the surface of water.

The hollow shell offers a relatively generous space for housing control circuits, flipper servos, a duplex wireless serial port communication module, the lithium battery pack, a sensory microcontroller, and a main microcontroller. The battery pack and servos are placed at the bottom of the shell to lower the center of gravity so that the vertical stability of the robot can be ensured. A pair of independent mechanical pectoral flippers capable of feathering motion, which is fixed on both sides of the body. Each joint is connected to a servo, which is utilized to control the rotational angle of each pectoral flipper.

A rotatable dorsal fin, which is installed on the top surface of waist cabinet, provides stability and assistance in orientation adjustment while swimming. The cross-sectional design of the rubber fluke that is attached to the caudal cabinet displays the characteristics of fusiform design. This special shape enhances the swimming performance of the robotic dolphin. With the cooperation of waist and caudal joints, a two-joint flapping is used to execute symmetrical dorsoventral oscillations in a sinusoidal fashion and generate lift-derived thrust.

Water quality multiprobe (JJ-Threeprobe-232) is fastened to the bottom of the robotic dolphin to collect the data of temperature, PH value, and conductivity. The robotic dolphin adopts distinctive modularity concept for easy installation,

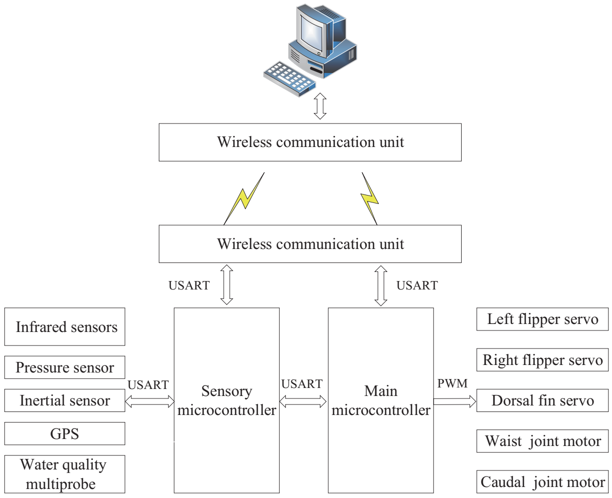

Fig. 3. Hardware architecture of the robotic dolphin.

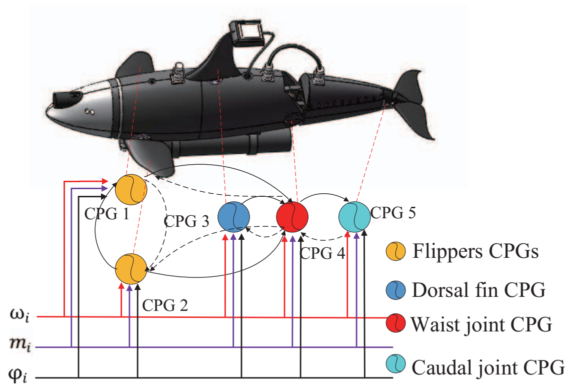

Fig. 4. Topology of the CPGs network used for the robotic dolphin.

the water quality multiprobe would be replaced according to the different tasks.

B. Hardware Architecture

In this paper, an embedded control system is employed to effectively manage multiple servos and DC motors, sensors, and peripherals. The hardware architecture of the robotic dolphin is shown in Fig. 3. A multiple-axis motion controller based on a high performance and lowpower dissipation microcontroller STM32F407 is employed to process varieties of function interface. Varieties of onboard sensors capture the robotic dolphin's attitude and in-situ water quality information and then transmit to the sensory microcontroller by USART. On one hand, a PC is used as a console, which is responsible for remote control and monitor of the robotic dolphin. A wireless communication module, radio frequency wireless transreceiver modules, i.e., RF 200, is required for the information interaction between the robotic dolphin and the console including commands and multi-sensors data. The control commands from the upper controller are transmitted to the main microcontroller and then control servos and DC motors. On the other hand, according to processed data from the sensory microcontroller, the main microcontroller can automatically adjust the motion mode of the robotic dolphin. This embedded system enable the robotic dolphin to both implement external inputs and closed-loop motion control aided by sensory information.

III. CPG-Based Locomotion Control

A. CPG Control Model

As identified by biologists, Central Pattern Generators are neural circuits mainly locate in the spinal cord of vertebrates or in relevant ganglia of invertebrates, which can produce coordinated oscillatory signals of different motion patterns, such as respiration, chewing, or leg movement during walking, without any rhythmic inputs from sensory feedback or from higher control centers [13]. As an outstanding online gait generator, it has been designed to realize multimodal locomotion for biomimetic robots [14], [15]. Conside the configuration of the developed robotic dolphin, a possible topology of the CPGs network is illustrated in Fig. 4. Specifically, a CPGs model allowing free adjustment of oscillation frequency, amplitude, and phase lags is employed to execute flexible swimming. The corresponding mathematic expression of the CPGs model can be shown as follows:

$$\begin{cases} \dot{x}_i = & -\omega_i y_i + x_i(m_i^2 - x_i^2 - y_i^2) \\ & +h_1(x_{i-1}\cos\varphi_i + y_{i-1}\sin\varphi_i) \\ \dot{y}_i = & \omega_i x_i + y_i(m_i^2 - x_i^2 - y_i^2) \\ & +h_2(x_{i+1}\sin\varphi_{i+1} + y_{i+1}\cos\varphi_{i+1}) \end{cases} \quad (1)$$

where the subscript i corresponds to the ith oscillator ($i = 1, \cdots, n$) and n indicates the total number of neural oscillators in the CPGs network. ω_i and m_i stand for the intrinsic oscillation frequency and amplitude of the ith oscillating neuron respectively. x_i and y_i denote the state variables of the i th oscillator. h_1 and h_2 are coupling weights that regulate the speed of convergence, φ_i means the phase lag of the output signals.

Notice that, in the interests of simplicity, the whole CPGs network employs nearest neighbor weak coupling principle. Through the coordinated control of multiple control surfaces, a diversity of propulsive modes such as forward swimming, turning maneuvers, diving/ascending motion, and braking are defined and implemented. The multimodal swimming gaits are schematically drawn in Fig. 5.

B. Forward Swimming

In order to thrust the dolphin through the water, the waist and the caudal joints are cooperated to implement symmetrical dorsoventral oscillations in the vertical plane with a sinusoidal fashion. The speed of the forward motion is adjusted by modulating oscillating frequency, amplitude, and phase lags. The output signals in a forward swimming are illustrated in Fig. 6, where m_4 = 30.7032, m_5 = 35.0787, h_1 = 4.0, h_2 = 5.0, $\varphi_4 = \varphi_5 = 90°$.

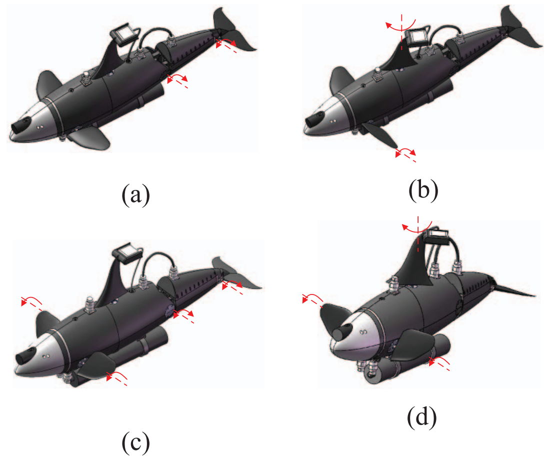

Fig. 5. Swimming gaits of the robotic dolphin. (a) Forward swimming, (b) Turning maneuvers, (c) Diving/Ascending, (d) Braking.

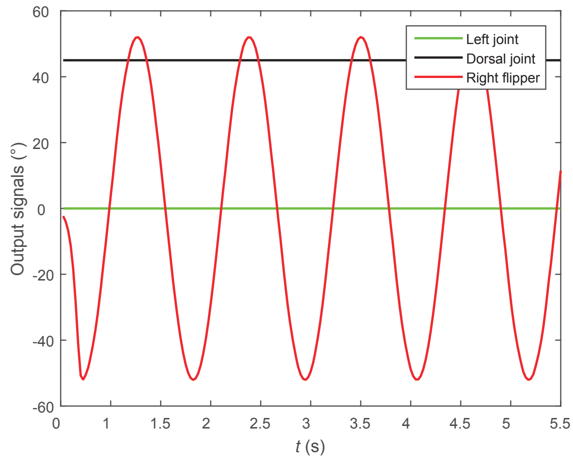

Fig. 7. The CPGs output signals in a turning swimming.

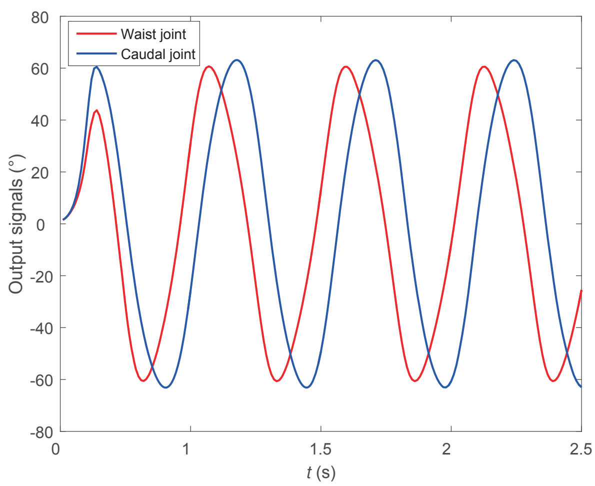

Fig. 6. Control signals for the waist and caudal joints in a forward swimming.

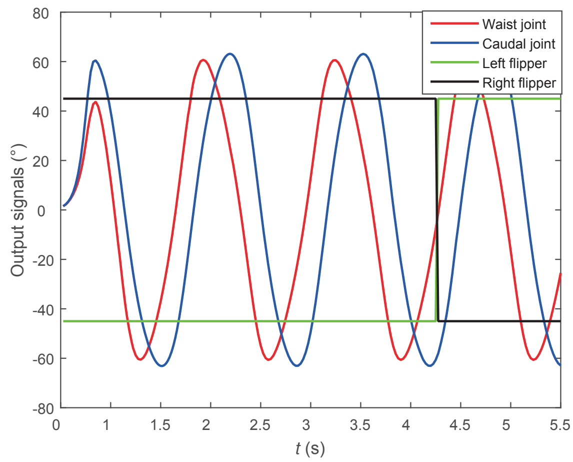

Fig. 8. The CPGs output signals in the submerging/ascending.

C. Turning Locomotion

Natural dolphins conduct turning maneuvers in the horizontal plane by lateral flexion of the anterior body, however, no yaw joint is included for the purpose of mechanical simplicity. The dolphin is equipped with artificial flippers to employ the asymmetric drive to accomplish planar turning. The dorsal fin, in those species that is unmoved, provides stability while swimming. As for the dolphin robot, the dorsal fin is designed for the purpose of auxiliary steering in the horizontal plane. When the robotic dolphin makes a right turn that is shown in Fig. 5 (b), the turning can be generated by the flapping movements of left flipper, at the same time, the dorsal fin turn towards the desired turning direction to increase upstream face. Fig. 7 shows the CPGs output signals for the turning locomotion.

D. Diving and Ascending

A pair of flippers are employed to achieve diving and surfacing, in which the magnitude and direction can be adjusted by modifying the flippers deflection. In particular, the robotic dolphin must maintain a certain speed of movement to actively adjust lift and drag. When the robotic dolphin is commanded to dive, the pitch angle of flippers should be set as shown in Fig. 5 (c). In that case the surrounding water will generate a downward force on the flippers, allowing the robotic dolphin to swim downwards. Because of mirror installation, the right flipper CPG has opposite phase with the left one so the CPGs output signals in the submerging/ascending is shown in Fig. 8.

IV. Experiment and Results

In order to verify the proposed control method and the three-dimension motion capability, some experiments are carried out in a swimming tank of 5.0 m ×4.0 m ×1.5 m (length×width×height) with still water. Some cameras are installed in the tank and are responsible for providing the in-situ environment information and the motion status information of the robotic dolphin in real time. At last, field testing is performed to verify the feasibility of the system.

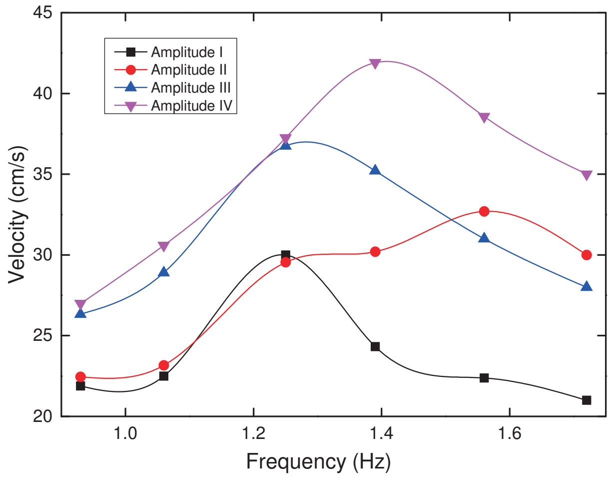

Fig. 9. Swimming speed evaluation with different frequencies, amplitudes, and phase lags, where Amplitude I (m_4 = 19.7032, m_5 = 35.0787, $\varphi_4 = \varphi_5$ = 70°), Amplitude II (m_4 = 19.7032, m_5 = 35.0787, $\varphi_4 = \varphi_5$ = 90°), Amplitude III (m_4 = 30.7032, m_5 = 35.0787, $\varphi_4 = \varphi_5$ = 70°), and Amplitude IV (m_4 = 30.7032, m_5 = 35.0787, $\varphi_4 = \varphi_5$ = 90°).

A. Experiments on Forward Swimming

The first experiment concerned the effect of oscillation frequency, amplitude, and phase lags during forward swimming. The commonly used method for speed control is the adjustment of the oscillation frequency and amplitude. Using (1), the phase lags also play a large part in speed control. As a demonstration, four swimming cases with various variables were examined. Fig. 9 gives an experimental comparison of forward speeds with different frequencies, amplitudes and phase lags. As could be observed in Fig. 9, with the increase of the frequency and amplitude, the forward speed was gradually increasing, and then began to decrease when the frequency reached a certain value (f = 1.25 Hz for I and III). This phenomenon may be due to insufficient servo torque output offered at higher frequencies. In general, under the same amplitude, with increasing frequency, the bigger phase lags, the faster swimming speed. The maximum swimming speed of the robotic dolphin was 0.42 m/s (corresponding to 0.56 BL/s, where BL is the abbreviation of body length) when f = 1.41 Hz.

B. Experiments on Turning Maneuvers

To ensure a stable turning performance and comparison, the robot was required to uninterruptedly perform a circular trajectory under the flapping frequency about 2 Hz, in which maneuverability related parameters were then estimated. The contrast experiments are depicted in Fig. 10. The collected data indicated that the turning radius in the Fig. 10 (a) was about 1.2 BL under the flippers plus dorsal fin turning mode which was better than the only used flippers turning mode with a turning radius about 1.4 BL in the Fig. 10 (b).

C. Experiments on Diving and Ascending

Considering that 3-D swimming can be viewed as a composition of yaw maneuvers and up-and-down motions, finally, experiment of diving and ascending was illustrated in Fig. 11. At the beginning of diving, the robot accelerated from stationary state and started from the right side of the surface of the tank. In the process of diving, the depth information was constantly monitored by the pressure sensor, when the submergence depth exceeded a certain value (parameter was set to 1.2 m) the robotic dolphin would change the pitch angle and start to ascend [see Fig. 11 from (d) to (f)]. When t = 5 s, the submergence depth exceeded a critical value and the robot was preparing to ascend and the robot climbed to the water surface at t = 10 s.

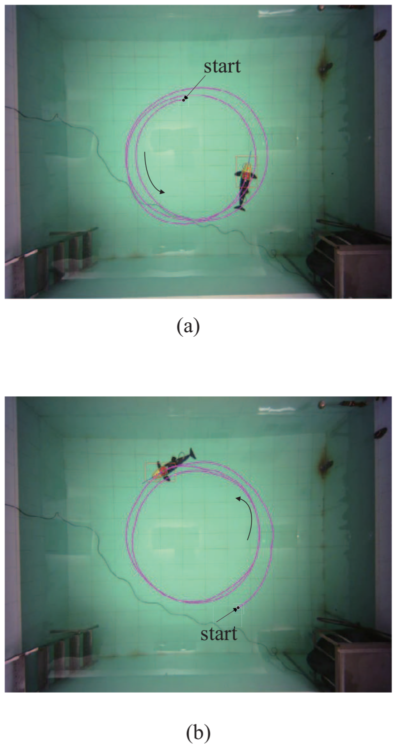

Fig. 10. The trajectory of the robotic dolphin performing a circular motion with different modes. (a) Turning with the dorsal fin (b) Turning without the deflecting dorsal fin.

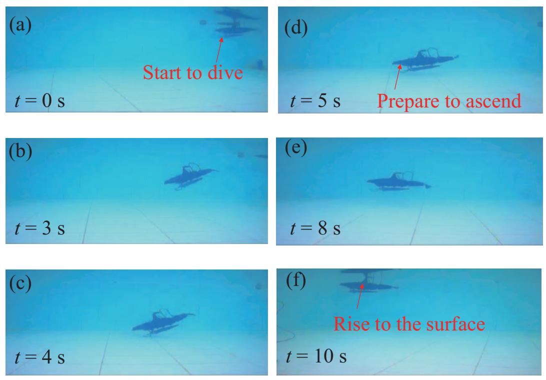

Fig. 11. Snapshot sequence of the diving and ascending with an arrangment from (a) to (f).

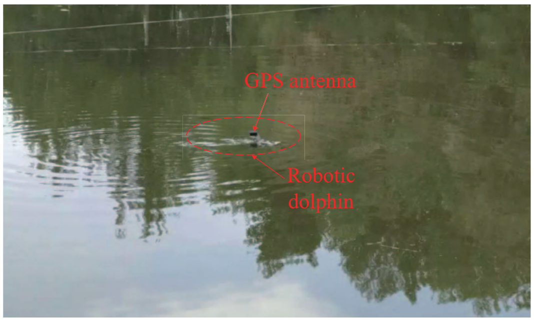

Fig. 12. Experiment snapshot of the water quality monitoring at a certain aquaculture center of naked carps in Qinghai Province.

D. Application Case

Water quality monitoring experiment can be regarded as a commission to inspect propulsion and maneuverability performance of the robotic dolphin. Remarkably, the water quality multiprobe can be replaced quickly according to the requirement of aquatic environment. Experiments were conducted in June 2016, at a certain aquaculture center of naked carps in Qinghai Province, China. In order to monitor the growing conditions of naked carps, aquatic environment parameters, such as temperature, PH value, and conductivity should be monitored constantly. By virtue of the robot's three-dimensional movement performance, in-situ water quality information from various depths is transmitted to the upper controller. The snapshot of the experiment is shown in Fig. 12. The experiment proved the feasibility of water quality monitoring based on the robotic dolphin.

E. Discussion

In this study, our newly developed robotic dolphin not only provides a repeatable test bed but also serves a practical application purpose, allowing the robot to monitor the water quality with water quality multiprobe. Particularly, the optimized physical design is considered to reduce drag and improve the swimming performance. Frequencies, amplitudes, and phase lags have marked impacts of propulsive speed, according to the influence of parameters adjustment on the swimming speed, it can be assumed that more optimized parameters applied to the robot may lead to faster speed. Remarkably, the maneuverability of the robotic dolphin, of course, is not as good as that of the multijoint robot with turning unit. However, the simplified mechanical configuration reduces the complexity of manufacturing technology and the robot that is ready for water quality monitoring and the turning maneuver meets the requirement for the wide expanse of aquatic environments. As an economical and effective water quality monitoring mode, the robotic dolphin will play an important role in the water safety protection and water emergency supervision.

V. Conclusion and Future Work

In this paper, we have developed a novel robotic dolphin for water quality monitoring. Concerning the dolphin-like swimming, the robotic dolphin could realize propulsive speed depending on the powerful posterior body and fluke, and could also achieve turning maneuvers according to the controllable pectoral fins and dorsal fin. A replaceable water quality multiprobe was fixed under the robot to obtain the in-situ water quality. Moreover, a bio-inspired CPG-based controller was built to improve the capability of multi-modal locomotion including forward swimming, backward swimming, turning, diving and surfacing. Finally, aquatic experiments in Qinghai Province verify the effectiveness of water quality monitoring based on the robotic dolphin.

The ongoing and future work will focus on the intelligent control for the robotic dolphin to monitor the water autonomously and also plan the swimming path according to the assigned task and complex underwater environment.

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