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Development and Control of Dolphin-like Underwater Vehicle

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Abstract— **This paper is concerned with prototype development and motion control of a dolphin-like underwater robot. The propulsion and maneuvering of the robotic dolphin are realized with the flapping motion of the mechanical flippers and the combined heaving and pitching motions of the fluke. Mechanical design and control of the flipper apparatus and the flexible tail mechanism are presented. Through coordinated control of the propulsors, several swimming movements are designed. Preliminary experimental results verify the effectiveness of the proposed design scheme.**

I. INTRODUCTION

Biorobotic autonomous underwater vehicle (AUV) has become one of the hot research topics in the last decade [1]. The driving motivation for this research is to unveil the underlying biological principles of marine propulsion and maneuvering and to incorporate this knowledge into nautical engineering practice. Contemporary AUV technology will benefit from this study for enhanced swimming performance such as high efficiency, great agility, station-keeping ability and reduced detection.

Majority of research work in this area have been focused on fish-like swimming and their engineered counterpart, robotic fish. In 1994, Triantafyllou *et al* pioneered the study of robotic fish by developing the well-known RoboTuna that propels with posterior flexible body and oscillating tail foils [2] [3]. Since then, various kinds of robotic fish have been developed around the world. Anderson *et al* built the mission-scale, autonomous underwater vehicle VCUUV that utilizes vorticity control mechanisms for propulsion and maneuvering [4]. Mason *et al* constructed a three-link carangiform swimmer for prediction of thrust generation with flapping tail [5]. Morgansen *et al* designed a fin-actuated underwater vehicle for agile maneuvering [6]. Hirata *et al* realized a series of robotic fish with different design objectives, from PF200 for up-down motion, PF300 for turning performance, to PF700 for high speed swimming [7]. In addition to the BCF (Body and Caudal Fin) mode swimming robots mentioned above, the MPF (Median and Paired Fin) mode has also been emulated in the design of underwater vehicles. Kato *et al* developed a pectoral fin driven robotic fish called "BlackBass" for precise maneuvering control [8]. To mimic the actual flexible fin of real fish, Low *et al* designed a fin-like mechanism that functions like a flexible membrane [9]. The authors previously designed a module-based robotic fish that propels with the tail fin and/or a pair of two-degree-of-freedom (2-DOF) pectoral fins [10].

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Dolphins, as one of the most enigmatic creatures in the ocean, have evolved an astonishing level of swimming capability. The grace that they glide through water and the ease that they burst out of the waves have always been a source of inspiration for nautical engineers. Although the first attempt to evaluate swimming energetics of dolphin, known as "Gray's Paradox" can be traced back to the 1930s, our understanding about the basic mechanism of drag reduction, thrust production and flow manipulation of dolphin are still limited. Compared with the extensive research in artificial fish-like system, innovative dolphin-inspired underwater robots are seldom. Nakashima *et al* developed a two-joint dolphin robot and its three-dimensional maneuverability was experimentally evaluated [11]. Dogangil *et al* carried out modelling, simulation and construction of a pneumatically-driven robotic dolphin [12].

This paper presents a novel underwater robots that mimics dolphin both in morphology and swimming motion. As a successor of our previous design of proof-of-concept version [13], this robotic dolphin is a highly sophisticated mechatronic system that involves mechanics, electronics, actuation, sensing and control technologies. Propulsion and maneuvering of the robotic dolphin are achieved with dorsoventral oscillation of the fluke and the flapping motion of the mechanical flippers. Since the propulsion and maneuvering is the basic locomotion ability of the robotic dolphin, this paper focuses on the mechanism design, analysis and control of the motion system.

The rest of the paper is organized as follows. Section II provides an overview of the robotic dolphin. Mechanism design of the motion system, including the mechanical flipper and the flexible tail are presented in Section III. Motion control algorithm and several swimming movements are addressed in Section IV. Preliminary experimental results are provided in Section V. Finally, Section VI concludes the paper with an outline of future work.

II. OVERVIEW OF ROBOTIC DOLPHIN

Design of the robotic dolphin is based on biological and hydrodynamic studies of swimming dolphins in nature [14]. A number of factors contribute to the excellent swimming of dolphin, such as morphological design, compliant skin,

Fig. 1. Prototype of biomimetic robotic dolphin.

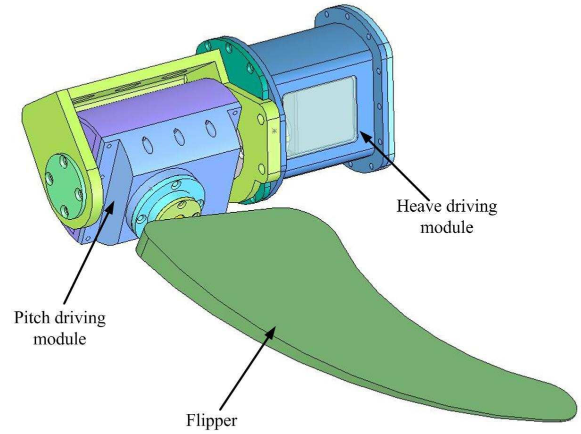

Fig. 2. Mechanical flipper apparatus.

swimming kinematics, behaviorial strategies, etc. To develop underwater robots with dolphin-like swimming performance, the best route is to copy the nature as exactly as possible, although the underlying mechanism has only been partially, or even poorly understood.

The robotic dolphin is designed to be a self-contained, free-swimming underwater vehicle that propels and maneuvers like a dolphin. The outer shape is an exact replica of white-sided dolphin and all the components are designed according to the hydrodynamic characteristic of swimming dolphin. The anterior part of the body is a rigid, streamlined hull which houses the onboard power, electronics and tail-driven mechanism. A pair of 2-DOF mechanical flippers are installed on the shoulder position of the robotic dolphin. The posterior part is a flexible mechanism that allows deflection in the vertical plane. A rubber coating covers the tail for waterproof purpose. Fig.1 shows the photograph of the robotic dolphin prototype. Basic technical specifications of the prototype are summarized in table I.

TABLE I
TECHNICAL SPECIFICATIONS OF ROBOTIC DOLPHIN PROTOTYPE

ITEM	VALUE
Dimension (L $\times$ W $\times$ H)	1.2m $\times$ 0.42m $\times$ 0.38m
Weight	22kg
Power Supply	DC, 24V, 5Ah
Actuator	DC Brush Motor & Servomotor
Operating Time	$\sim$ 1 Hour
Operating Mode	Radio Control, 444MHz

III. MECHANISM DESIGN OF ROBOTIC DOLPHIN

Of primary importance is the design and development of mechanism for propulsion and maneuvering. Two mechanisms have been implemented to effect swimming locomotion of the robotic dolphin, the mechanical flipper and the flexible tail.

A. Mechanical Flipper

Flippers are used by dolphin to enhance stability in fast swimming and to generate maneuvering moments in cluttered environment. Various movements can be performed by the flipper, including protraction, retraction, adduction, abduction, and rotation. Since the flipper is actively controlled musculoskeletal system with multi degrees of freedom, it is hard to realize such mobility with mechanical flipper. With two degrees of freedom, two types of oscillatory movements can be realized, the drag-based rowing and the lift-based flapping. In rowing action, the flippers move backward broadside and are brought forward edgewise. The thrust is generated only during the backward stroke and is discontinuous as a result. The flapping motion involves the dorsoventral oscillation of the flippers and both the upstroke and downstroke generate relatively large lift forces. Since the flapping motion generates larger, more continuous, and more efficient thrust than rowing motion, it is realized on the robotic dolphin.

A module-based approach is utilized in the design of the mechanical flipper. Two modules are employed to generate the synchronized heaving and pitching motion of the flipper. Each module is waterproofed separately with O-rings and grease. The module for heaving motion remains stationary relative to the body of robotic dolphin and the module for pitching motion rotates about the axis of the heaving module. The actuator inside of the modules is Hitec HS-5995 servomotor, which allows rotation range of $180°$. The flipper is connected to the rotation shaft of the pitching module and the whole mechanical flipper apparatus is attached to the body of robotic dolphin. Fig.2 shows the mechanical configuration of the mechanical flipper.

B. Tail Structure

The swimming motion of dolphin is analogous to the thunniform mode of fish swimming, in which the thrust is generated primarily with a high aspect ratio, crescent-shaped caudal fin. The vertical oscillations of dolphin are confined to the posterior one-third of the body and the fluke undergoes a combined pitching and heaving motion, tracing a sinusoidal pathway that is symmetrical about the longitudinal axis of the body and in time [14]. An important kinematic parameter that severely affects the propulsive efficiency is attack angle,

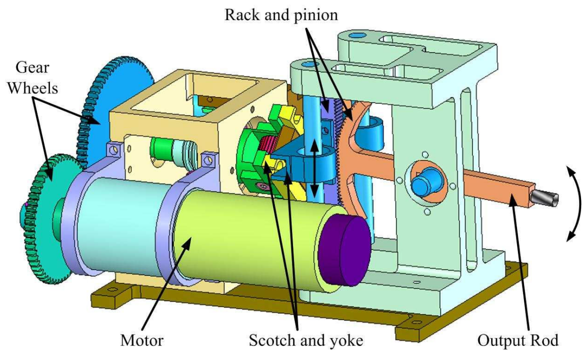

Fig. 3. Illustration of oscillation-output mechanism.

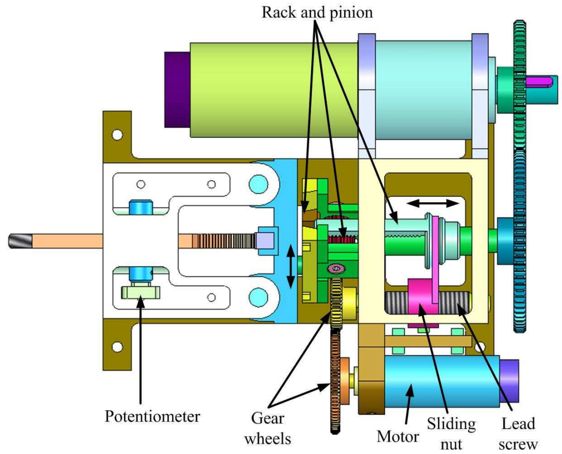

Fig. 4. Illustration of amplitude-adjusting mechanism.

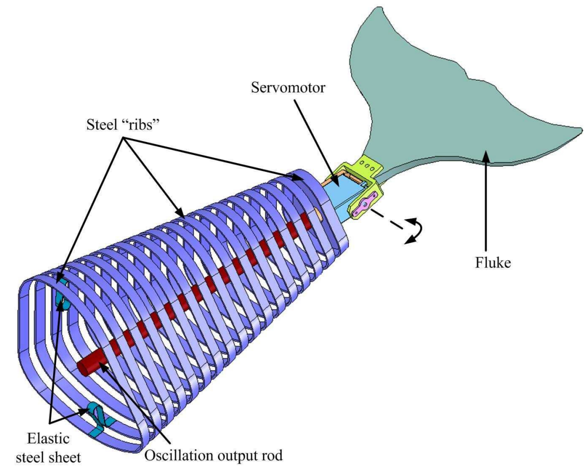

Fig. 5. Tail exostructure and fluke driven mechanism.

which is defined as the angle between the tangent of the fluke's path and the axis of the fluke's chord. The heaving and pitching motions change attack angle to ensure effective thrust generation throughout the stroke cycle [14].

The posterior part of the robotic dolphin is modelled as a two-joint mechanism, which allows independent control of the heaving and pitching motions. Control of these motions require the frequency, amplitude and the phase difference between them to be adjustable. The heave of the tail portion is actuated by DC brush motor, while the fluke pitch which requires less torque is realized with servomotors. A direct way to achieve sinusoidal oscillation with DC motor is through reciprocating rotation with precise motion control circuit. However, this method requires much computing power and is not energy efficient. Many mechanisms converts rotatory motion into reciprocating motion, among which scotch-yoke mechanism can deliver harmonic motion. In this research, a modified scotch-yoke mechanism that allows amplitude adjustment is designed for the tail heave movement of the robotic dolphin.

The tail driven mechanism is a complicated mechanical device that comprised of two transmission systems, the oscillation-output mechanism and the amplitude-adjusting mechanism. The oscillation-output mechanism is driven by a 150W Maxon DC motor. The motor turns two gear wheels, which in turn move the scotch-yoke mechanism to output harmonic linear motion. A rack is connected with the yoke, so that the reciprocating linear motion can be converted to reciprocating of a pinion. The output rod connected with the pinion can finally oscillates in a harmonic manner. Fig. 3 illustrates the oscillation-output mechanism. In order to regulate the amplitude of the oscillation-output mechanism, the crank radius in the scotch-yoke mechanism should be adjustable. The amplitude-adjusting mechanism driven by a 20W Maxon DC motor serves as a strategy for heave amplitude adjustment. The rotary motion of the gear wheels, which is connected with the motor is converted to linear motion using lead screw transmission. The sliding nut push a rack and pinion mechanism that rotates with the crank, which also is a rack. These two racks are perpendicularly fixed around the pinion, hence the linear motion of one rack will lead to the motion of another rack through the transmission of the pinion. The rotation of the motor can thus regulate the crank radius through the transmission system. In addition, a infrared sensor is mounted at each end of the lead screw to detect the position limit of the sliding nut. Fig. 4 shows the amplitude-adjusting mechanism.

The pitching motion of the fluke is driven directly by a Hitec HS-5995 servomotor. The fluke rotates about the axis of the servomotor, while the servomotor is fixed with the output rod of the tail driven mechanism. The exostructure of the tail is composed of steel "ribs" which are connected by elastic steel sheets. The biggest and smallest "ribs" are connected with the body and the servomotor, respectively. As energy storage component, the elastic steel sheets smooth the curvature of the tail and increase the propulsive efficiency of the posterior body to some degree. The oscillation output rod run through the steel "ribs", acting as the backbone of the tail structure. Fig.5 shows the tail exostructure and the fluke driven mechanism.

IV. MOTION CONTROL OF ROBOTIC DOLPHIN

A. Motion Control of Flippers

Extensive studies has been performed on the kinematics, hydrodynamics and morphology of pectoral fin swimming in fishes [15] and biomimetic flapping foils that emulate the motions of penguin wings have been shown to generate large lifting forces [16]. The mechanical flipper of the robotic dolphin driven by two perpendicularly fixed servomotors undergoes a simultaneous heaving and pitching motion, which is analogous to the aerial flight of insects and birds. Sinusoidal motions are implemented for the two degrees of freedom, which is a regular control strategy for three-dimensional flapping foils.

The heaving and pitching motions of the left flipper are defined respectively as:

$$\theta_{lh}(t) = A_{lh} sin(2\pi f_l t) \tag{1}$$

$$\theta_{lp}(t) = \phi_{lp} + A_{lp} sin(2\pi f_l t + \varphi_l) \tag{2}$$

where $\theta_{lh}(t)$ and $\theta_{lp}(t)$ correspond to the angular position of the heaving and pitching axes of left flipper at time t , ϕ_{lp} denotes the angular bias of pitching motion, A_{lh} and A_{lp} are amplitudes, f_l is the frequency and φ_l is the phase difference.

Since variations in pitch bias ϕ_{lp} have significant effect on the production of hydrodynamic forces, it is used as a strategy for maneuvering and three-dimensional swimming of the robotic dolphin. The direction of the thrust generated by the flipper depends on the phase difference φ_l and the magnitude of the thrust can be adjusted by variation of frequency and amplitudes.

Accordingly, the motion of the right pectoral fin can be described as:

$$\theta_{rh}(t) = A_{rh} sin(2\pi f_r t) \tag{3}$$

$$\theta_{rp}(t) = \phi_{rp} + A_{rp} sin(2\pi f_r t + \varphi_r) \tag{4}$$

B. Motion Control of Tail Mechanism

Propulsive motion of a dolphin can be depicted as vertical oscillation of the body and the fluke. The periodic excursions of the body center-line is approximately described by Romanenko [17] as:

$$h(x_n, t) = h_T(0.21 - 0.66x_n + 1.1x_n^2 + 0.35x_n^8) sin(2\pi f t) \tag{5}$$

where h_T is the maximal vertical excursion of the fluke, $x_n = x/L$ is the longitudinal coordinate measured from the beak divided by the animal's length L, f is the tail beat frequency and t is the time. Based upon the kinematic model, the minimum amplitude occurs at the shoulder and slight perturbations exist at the anterior end of the dolphin, which can be explained as a result of the large moment generated about the center of mass by the fluke. To generate the dorsoventral movement of dolphin, the best way is to emulate the propulsive model with multiple concatenated rotating joints. With the two-joint tail mechanism, it is hard to fit the body curve exactly. However, with proper tuning of the phase shift of heaving and pitching motions, thrust can be generated effectively. In addition, the smooth function of the flexible tail exostructure make possible that the body curve exhibited by the robotic dolphin will not substantially deviate from that of biological dolphin.

Through transmission of the tail driven mechanism, the constant speed rotation of the DC motor is converted to the sinusoidal heaving motion of the tail, which can be described by the following equation:

$$\theta_{th}(t) = A_{th} sin(2\pi f_t t) \tag{6}$$

where $\theta_{th}(t)$ is the angular position of the oscillation output rod, A_{th} is the heaving amplitude that can be modulated by the amplitude-adjusting mechanism, and f_t is the oscillation frequency that is determined by the rotation speed of the DC motor.

The pitching motion of the fluke follows the heaving motion in a sinusoidal manner. To detect the phase of the heaving motion, a potentiometer is installed at the rotating axis of the oscillation output rod. At each control instant over a period, the angular position of the oscillation output rod is computed with the following equation:

$$\psi = arcsin(\frac{\theta}{A_{th}}) \tag{7}$$

where θ is the sampled angular value and A_{th} is the heaving amplitude. So that the angular position of the servomotor can be computed as:

$$\theta_{tp} = A_{tp} sin(\psi + \varphi_t) \tag{8}$$

where θ_{tp} is the the angular position of the pitching motion at each control interval, A_{tp} is the pitching amplitude and φ_t is the phase difference between the heaving and pitching motions. With the control algorithm described above, the heaving and pitching motions will oscillate at the same frequency with a prescribed phase shift between them.

C. Typical Swimming Movements

Dolphins in nature exhibit various swimming movements such as sustained and burst swimming, powered and unpowered turning, diving, gliding, corkscrewing and even acrobatic aerial swirling. Both the mechanical flippers and the fluke can be used to generate thrust for the robotic dolphin and through the coordinated control of the propulsors, several basic swimming movements can be realized. However, since the swimming motion of the robotic dolphin involves complicated hydrodynamics, no effective analytical method can be used for swimming movement design. For a specific swimming pattern, trial and error procedure should be conducted with the experimental and numerical studies in the area of biomimetic flapping foils as a guide. With the proposed design scheme, the following swimming movements have been designed:

1) *Fluke-based Forward Swimming:*

The fluke, as the primary locomotion structure of robotic dolphin can generate large thrust for propulsion. By actuating the joints at the tail, the robotic dolphin can swim in a straight line. During this kind of movement, the flippers should be held parallel to the horizontal plane to enhance stability and to generate lift forces.

2) *Flipper-based Forward and Backward Swimming:*

Synchronized movements of the mechanical flipper on both sides can generate symmetric propulsive forces. To generate anteriorly directed thrust the phase differences are in the range of 0 and 180°, while for phase differences between $-180°$ and 0 backward swimming can be realized. The parameters on one side should equal the corresponding parameters on the other side in order for the thrust on both sides to be equal.

3) *Turning in the Vertical Plane:*

Due to the orientation of the fluke, dolphins can turn most effectively in the vertical plane. The robotic dolphin can execute vertical turning by asymmetric oscillation of the tail about the longitudinal axis of the body. Since the scotch-yoke mechanism outputs symmetric oscillation with constant rotation input in one direction, to realize asymmetric oscillation the motor should rotates reciprocatingly with amplitude not enough to produce a whole oscillation cycle at the output rod. In this movement, the tail no only provides the thrust but also produces a nonzero time-averaged torque that will cause a change in vertical heading direction.

4) *Turning in the Horizontal Plane:*

Dolphins turn in the horizontal plane by lateral flexion of the head, adduction and rotation of the flippers. No mechanism has been designed for lateral flexion of the robotic dolphin, so that the mechanical flippers act as the sole means for horizontal maneuvers. The differentiation of hydrodynamic forces between the mechanical flippers will cause a yawing moment. An effective method to execute turning in the horizontal plane with flippers is to produce anteriorly directed force on one side and posteriorly directed force on the other side.

5) *Submerging and Ascending:*

The robotic dolphin achieves three-dimensional motion by adjusting the attack angle of the flippers. As a precondition, the robotic dolphin should attain a forward swimming speed. The inclined flipper will cause a force that can be analyzed into a drag component and a positive or negative lift component. The attack angle of the flipper on each side should take the same value in order not to generate yawing or rolling moments.

6) *Braking:*

Braking maneuvers are used by dolphin in response to stimuli in front of them and also in the course of natural behaviors such as feeding. The robotic dolphin brakes through sudden rotation of the flippers to a position perpendicular to the body. The drag caused by the flippers decelerates and eventually stops the motion of the robotic dolphin.

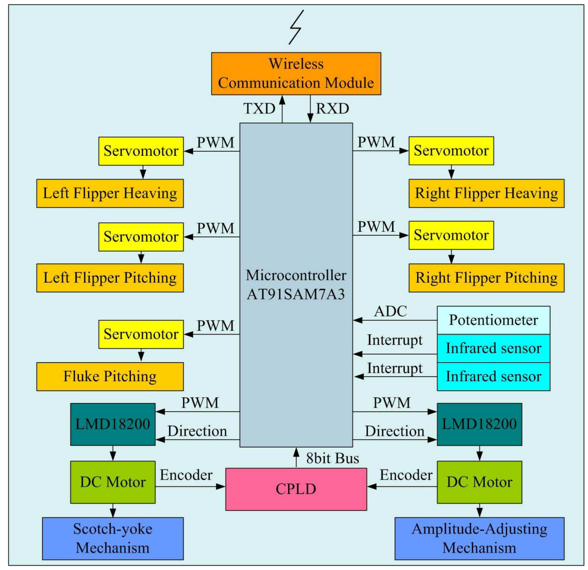

Fig. 6. Architecture of the control system.

V. CONTROL SYSTEM IMPLEMENTATION AND EXPERIMENTAL RESULTS

A. *Motion Control System*

Motion control of the robotic dolphin is achieved with the microcontroller unit AT91SAM7A3 that incorporates a high-performance 32-bit RISC, ARM7TDMI processor and a wide range of peripherals from ATMEL Corporation. For information exchange with the upper level controller, a duplex wireless communication module is connected with the controller through UART port. The swimming control algorithm are programmed into the flash memory within the microcontroller and the robotic dolphin executes the corresponding movements based upon the parameters received from the upper-level controller. Fig.6 illustrates architecture of the control system.

The R/C servomotors that drive the mechanical flippers and the pitching motion of the fluke, have internal position feedback and the degree of the turn of the axis depends upon the duty cycle of the input PWM (Pulse Width Modulation) signal. The microcontroller generates five PWM signals to control the motion of the joints and receives no feedback signal.

The DC motors at the tail mechanism are driven by H-bridge chips LMD18200 from National Semiconductor Corporation. The microcontroller provides PWM and direction signals for control of the motors. A shaft encoder of 1000 resolution is mounted at the rear of each motor and the quadrature output signals are connected to a CPLD that determines the position and speed of the motors. The microcontroller receives the feedback information from the CPLD and implements PID algorithm for close loop control of the motors. In addition, the output of the potentiometer are sampled by the Analog-to-Digital Converter (ADC) of the microcontroller for control of fluke pitching. The limit sensors of the amplitude-adjusting mechanism trigger exter-

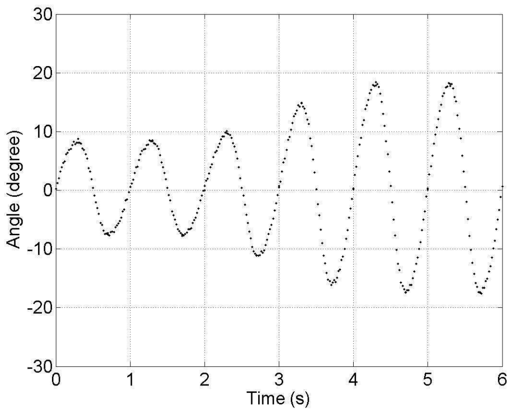

Fig. 7. Sampled angular value of potentiometer.

nal interrupt of the microcontroller, so that the motor can stop at the positions with largest and smallest amplitude.

B. Prototype Testing

Experiments with the robotic dolphin have been scheduled in two stages: off-water test stage and underwater test stage. To date, off-water tests have been conducted and underwater tests will be carried out after the robotic dolphin has been fully waterproofed.

Off-water tests focus on the performance of the tail mechanism. Fig. 7 shows the sampled angular value of the potentiometer at the axis of oscillation output rod over 6 seconds. The DC motor is commanded to rotate at speed of 100 rounds per minute and after the transmission of the gear sets of 5:3 ratio, the output rod oscillates at 1 Hz. The amplitude-adjusting mechanism starts at 2.0s to change the amplitude of the oscillation and stops at 4.0s. It is noticeable from the figure that the oscillation at upward direction is slower than that at downward direction, which is caused by asymmetric gravity load to the motor. The effect will be reduced in underwater tests since the buoyancy can cancel out most of the gravity.

VI. CONCLUSIONS AND FUTURE WORK

This paper presented a novel biorobotic underwater vehicle that propels and maneuvers like a dolphin. A pair of 2-DOF mechanical flippers allow flapping motion that generates both propulsion and meneuvering forces. The tail-driven mechanism consisting of scotch-yoke mechanism and amplitude-adjusting mechanism provides the heaving motion of the fluke, while the servomotor at the peduncle allows attack angle control of the tail hydrofoil. Swimming movements that involve the motion of the flippers and fluke enable excellent mobility of the robotic dolphin. Off-water experiments demonstrated the effectiveness of the proposed design scheme.

Underwater experiments with the robotic dolphin will be conducted in the near future. Hydrodynamic modelling should be done for improvement of the mobility and energy efficiency. For practical applications, more technical hurdles such as underwater communication, long duration and autonomous operation will be addressed.

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