International Journal of Offshore and Polar Engineering (ISSN 1053-5381)

Vol. 23, No. 3, September 2013, pp. 166–171

http://www.isope.org/publications

Depth Control for Robotic Dolphin Based on Fuzzy PID Control

Fei Shen, Zhiqiang Cao, Chao Zhou and De Xu
Institute of Automation, Chinese Academy of Sciences, Beijing, China

Nong Gu
Center for Intelligent Systems Research, Deakin University, Victoria, Australia

In this paper, the depth control for a robotic dolphin is considered. The structure of the robotic dolphin is firstly designed based on the analysis of stable conditions on the motions of biological fish and dolphins. Our pitching motion analysis indicates that the movement distance of balance weight can be employed for depth control. Considering the nonlinear model in depth control and the volume variation of the rubber skin due to water pressure, a fuzzy PID controller is proposed to realize the depth control. Fuzzy controller 1 is utilized to compensate for the big error with fast response. To eliminate steady-state error caused by buoyancy change, fuzzy controller 2 and an accumulator are activated by the intelligent switch when necessary. The experimental results verify the effectiveness of the proposed controller.

INTRODUCTION

Underwater biomimetic robotics, such as robotic fish and robotic dolphins, have received more and more attention in recent years. Compared to fish, dolphins are superior swimmers due to their horizontal caudal fins (flukes) along the longitudinal main bodies. It is observed that the propulsive efficiency of dolphins can reach up to 0.75–0.9 and the maximum swimming speed is over 11 m/s. Moreover, dolphins can also achieve excellent turning maneuverability in that they can rotate their bodies with an angular speed of 450 deg/s and with turning radii down to 11–17% of body length (BL) (Fish and Rohr, 1999).

These interesting features motivate many researchers to create dolphin-like robots, focusing on hydrodynamics analysis, mechatronic design and control schemes. These efforts include the two-joint robotic dolphin (Nakashima and Ono, 2002; Nakashima et al., 2006), the four-joint pneumatic robotic dolphin (Dogangil et al., 2005), the five-joint robotic dolphin with a pair of 2 degrees-of-freedom (DOF) pectoral fins as well as the robotic dolphin with a two-motor-driven scotch yoke mechanism (Yu et al., 2007; Yu et al., 2009), and our multi-link robotic dolphin with 3-DOF flippers (Shen et al., 2011). Some control schemes on propulsion, turning motion and loop-the-loop motion were developed for these prototypes (Nakashima et al., 2006; Yu et al., 2007; Shen et al., 2011). In addition, control algorithms for the pitching motion are of special interest as they can improve the maneuverability significantly. The pectoral fin method (Zhang et al., 2007; Liu et al., 2005) and the barycenter adjustment method (Zhou et al., 2006; Yu et al., 2011) were proposed for realizing the pitching motion. However, the research on depth control is relatively rare, especially for robotic dolphins. In fact, keeping the robotic dolphin at a certain depth to improve environmental adaptability has great potential applications. In this paper, we propose a new depth control method to address this problem.

From the engineering perspective, some guidelines to achieve stability of the robotic dolphin are firstly illustrated by taking advantage of biological fish and dolphins. The structure of the robotic dolphin with a barycenter adjustment mechanism is then designed to realize the pitching motion that is the foundation of depth control. Our pitching motion analysis indicates that one can employ the movement distance of balance weight to control the depth and the relationship between these two variables is nonlinear. This nonlinearity combined with the complexity of hydrodynamics make the model-based control method infeasible for the depth control. In this paper, fuzzy logic control is considered as it does not require an accurate model and *a priori* knowledge could be exploited to ensure reliability of the robotic dolphin. Currently, fuzzy control has been widely studied, including robust self-tuning fuzzy tracker (Fang et al., 2011) and formula-based fuzzy PI controller (Kumar et al., 2011). The challenges we face include the nonlinearity model of the robotic dolphin, periodic fluctuation of depth caused by the dorsal-ventral propulsive movement and the volume variation of the rubber skin due to water pressure. To address these challenges, a fuzzy PID depth controller is proposed in this paper. This controller employs fuzzy controller 1 to reduce the initial error with fast response. In addition, fuzzy controller 2 and an accumulator, which can be regarded as an integral controller, are used to eliminate steady-state error caused by volume variation. To avoid integration saturation that is easily caused by limited range of control variable, an intelligent switch is designed to activate fuzzy controller 2 when necessary.

THE STRUCTURE OF ROBOTIC DOLPHIN AND PITCHING MOTION ANALYSIS

The Stability Concerning Biological Fish and Dolphin

Some concepts about static stability are firstly introduced. Small turbulence may force an object to deviate from its balance position. As soon as the disturbance disappears, this object is static stable if it has the motional tendency of recovering its original balance position. Otherwise, it presents either static unstable if continuous deviations are observed, or neutral stable if the object stays at a new position after this disturbance.

Some observations about the stability of fish and dolphins are summarized as follows:

(1) Most bony fish are static unstable as their buoyancy centers are located below the gravity centers (Lauder and Madden, 2006).

Received November 8, 2012; revised manuscript received by the editors April 11, 2013. The original version was submitted directly to the Journal.
KEY WORDS: Robotic dolphin, depth control, barycenter adjustment, fuzzy PID control.

Such a static unstable nature leads to some advantages such as good maneuverability. However, considerable energy is required to compensate for this instability as fish have to swing their fins constantly to maintain the changing balance position.

(2) Dolphins are more like neutral stable creatures, because their buoyancy center and gravity center share almost the same position (Fish, 2002). The neutral stability is the root cause why the dolphin can roll, side-swim, swim upside-down, and barrel-roll flexibly. Dolphins rely on two different methods to maintain stability and maneuverability, which are active control and passive control (Fish and Lauder, 2006). The former needs active involvement of the caudal fin or pectoral fin while the latter benefits from their morphological features, which do not demand extra energy.

We note that it is more desirable to design a static stable system from the engineering perspective, since stability is always the first priority in robotic system design. To achieve this, the following guidelines are implemented in our robotic dolphin system:

(1) The center of gravity should be below the center of buoyancy. This will guarantee the designed system to be static stable. However, the significant loss in maneuverability will be unavoidable if the center of gravity is far below that of buoyancy.

(2) The total gravity equals the buoyancy.

(3) The gravity center and buoyancy center are on the same plumb line, which perpendicularly intersects with the medial axis of the robotic dolphin.

The Structure of Robotic Dolphin

The robotic dolphin, shown in Fig. 1, consists of an anterior body and rear body part.

The rear body part includes 4 joints driven by servos, a fluke, a peduncle and a rubber skin. Among the 4 joints, joints 1 to 3 are used to propel the body of the robotic dolphin and the turning joint is employed for yawing. The fluke and joint 3 are connected by the peduncle. The rubber skin is designed to smooth the curvature of the tail and reduce drag to some extent.

The anterior body part is mainly composed of the hull, barycenter adjustment mechanism and electronic units. The electronic units include the wireless module (B1), GPS module (B2), control board (B3), power unit (B4) and a pressure sensor measuring the depth of the water. The barycenter adjustment mechanism is fixed in the hull of the head to realize the pitching motion of the dolphin body.

The barycenter adjustment mechanism, as shown in Fig. 2, mainly consists of a stepping motor, photoelectric encoder, balance weight, synchronous belt, two drive gears, a screw shaft, two supporting guideways and two limit switches.

The output shaft of the motor connects directly with the screw shaft and the balance weight links with the nut on the screw shaft. When the screw shaft is rotated by the stepping motor, the balance weight will move with the nut along the axial direction of the screw shaft. The balance weight may generate vertical pressure on the screw shaft, which will damage the stepping motor. To avoid this damage, two supporting guideways are fixed at the bottom of

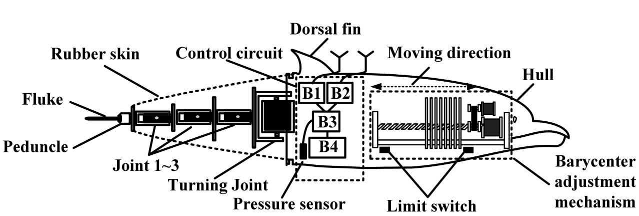

Fig. 1 Structure diagram of robotic dolphin

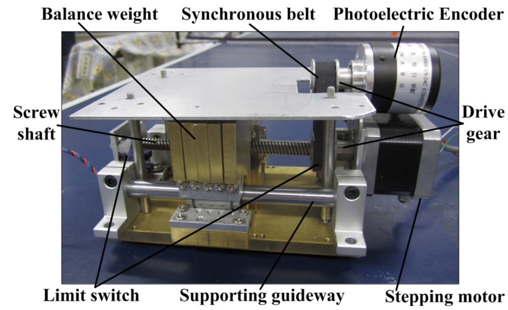

Fig. 2 Barycenter adjustment mechanism

the balance weight. The balance weight consists of several copper blocks, whose number shall be adjusted according to the needs. The movement distance of the balance weight is measured by a photoelectric encoder, which is connected with the screw shaft through synchronous belt and drive gears. When the screw shaft is driven to rotate by the stepping motor, the photoelectric encoder also rotates via the synchronous belt. The movement distance of the balance weight can be easily calculated by the rotation angle of the encoder. To ensure the safety of the stepping motor, two limit switches are fixed separately at the two ends of the supporting guideways to limit the output of the stepping motor.

Pitching Motion Analysis of Robotic Dolphin

As shown in Fig. 3, two coordinate frames, $O_0x_0y_0z_0$ and $O_1x_1y_1z_1$, are established. The former is the inertial coordinate frame and the latter is the coordinate frame attached to the robotic dolphin, where O_1 is the gravity center of the robotic dolphin without pitching motion, O_1x_1 is the horizontal medial axis of the robotic dolphin, O_1y_1 is the vertical one and O_1z_1 is perpendicular to $O_1x_1y_1$ plane according to the right-hand rule. In addition, A_2 and A_3 are labeled as gravity center and buoyancy center of whole robotic dolphin, respectively. A_4 and A_5 denote the gravity center of the robotic dolphin excluding the balance weight and the gravity center of balance weight, respectively.

When the robotic dolphin is just completely submerged in the water, the coordinates of O_1, A_2, A_3, A_4 and A_5 in $O_0x_0y_0z_0$ are (x, y, z), (x, y, z), $(x, y+h, z)$, $(x-a, y, z)$ and $(x+b, y, z)$,

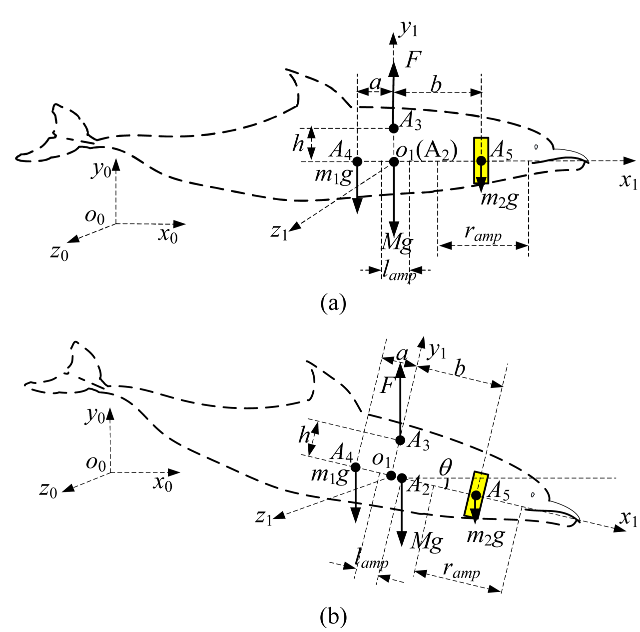

Fig. 3 Pitching motion analysis of robotic dolphin

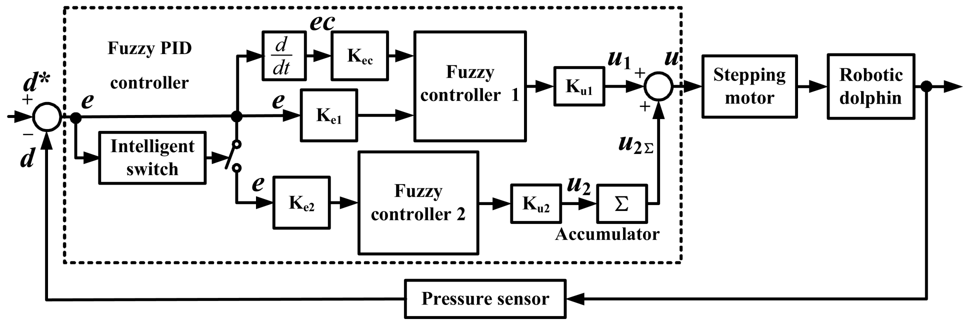

Fig. 4 The depth control system of robotic dolphin based on fuzzy PID

respectively, where h is the distance between A_2 and A_3, a is the distance between A_2 and A_4 and b is the distance between A_2 and A_5. When A_5 moves from point $(x+b, y, z)$ to point $(x+b+r(t), y, z)$, A_2 will move from point (x, y, z) to point $(x+l(t), y, z)$. Let $r(t) \in [-r_{amp}/2, r_{amp}/2]$ denote the movement distance of the balance weight and l(t) denote the change in magnitude of the gravity center of the robotic dolphin, where r_{amp} is the movement range of the balance weight. Then, we have:

$$l(t) = \frac{m_2 r(t)}{m_1 + m_2} \tag{1}$$

where m_1 is the mass of the robotic dolphin excluding the balance weight and m_2 is the mass of the balance weight. Due to the movement of the balance weight, the gravity center of the whole robotic dolphin also moves. In this case, A_2 and A_3 are no longer on the same plumb line and the pitching moment is produced. Figure 3b shows the force analysis when the robotic dolphin reaches steady state. From this figure, we can obtain the pitching angle θ(t) at the steady state as:

$$\theta(t) = \arctan\frac{l(t)}{h} = \arctan\frac{m_2 r(t)}{(m_1 + m_2)h} \tag{2}$$

The above pitching motion analysis is based on static situation. When the robotic dolphin moves up or down with a swimming velocity v(t), it will have a component v_y(t) along $O_0 y_0$:

$$v_y(t) = v(t)\sin(\theta(t)) \tag{3}$$

The swimming velocity v(t) is impacted by not only the oscillation frequency and amplitude of robotic dolphin tail, but also the pitching angle θ(t). For a different pitching angle, the lateral resistance acting on the robotic dolphin is different. Thus, v(t) is a function of θ(t) when the oscillation frequency and amplitude are constant. In this case, measured depth d(t) can be described as:

$$\begin{aligned} d(t) &= \int_0^t v(t, \theta(t))\sin(\theta(t))dt + d_0 \\ &= \int_0^t v\left(t, \arctan\frac{m_2 r(t)}{(m_1+m_2)h}\right) \\ &\quad \times \sin\left(\arctan\frac{m_2 r(t)}{(m_1+m_2)h}\right)dt + d_0 \end{aligned} \tag{4}$$

where d_0 is the initial depth of the robotic dolphin.

Based on the above analysis, two conclusions can be drawn:

(1) From Eq. 2, one can see that the distance h is not only a good indicator of the robotic dolphin's pitching stability but also that of pitching maneuverability. If h approaches zero, the robotic dolphin becomes neutral stable and any tiny movement of the balance weight leads to instability. When h is large, the robotic dolphin enjoys higher pitching stability. However, a significant decrease in the pitching angle θ(t) can be observed due to the larger contribution of h in the denominator of Eq. 2. Therefore, it is essential to choose an appropriate value of h to make a balanced solution of the stability and the maneuverability.

(2) Equation 4 indicates that the robotic dolphin depth d(t) can be controlled by adjusting the position of the balance weight r(t) with a constant oscillation frequency and amplitude of its tail. The relationship between r(t) and d(t) is nonlinear.

Due to the nonlinear relationship between the control variable (the movement distance of balance weight) and the target variable (the depth of robotic dolphin) and the complexity of hydrodynamics, the model-based controllers may be too "expensive" in terms of the complexity of algorithms. Compared with traditional model-based controllers, fuzzy logic control has many advantages. It requires less knowledge about the control process and can be upgraded more easily by adding new reasoning rules. In the following, we present a fuzzy-based approach to solve the depth control problem.

THE DEPTH CONTROL OF ROBOTIC DOLPHIN BASED ON FUZZY PID CONTROL

The Depth Control System

The following facts are considered in developing the depth control:

(1) The depth control of the robotic dolphin shall be described by a nonlinear model.

(2) The dorsal-ventral propulsive movement of the robotic dolphin makes the depth fluctuate periodically when it pitches.

(3) The volume covered by the rubber skin may change continuously due to the variation of water pressure, especially when the robotic dolphin pitches. This varying volume may result in a change in the buoyancy, thus producing a steady-state error.

Considering these facts, we adopt a fuzzy PID controller for the robotic dolphin, which is shown in Fig. 4. The system mainly includes an intelligent switch, fuzzy controller 1, fuzzy controller 2, an accumulator, a stepping motor and a pressure sensor. The input of the fuzzy PID controller is the depth error. The output of the fuzzy PID controller, which is the sum of output of fuzzy controller 1 and accumulator, is fed into the stepping motor for changing the movement distance of the balance weight. Essentially, fuzzy controller 1 is equivalent to a nonlinear PD controller, which can produce faster response and compensate for the big error, whereas fuzzy controller 2 and the accumulator can be regarded as an integral controller, which aims to eliminate the steady-state error introduced by buoyancy changes. The intelligent switch can activate fuzzy controller 2 when necessary to avoid integration saturation. It is noted that there also exist other solutions to solve the problem of the tail volume change with depth. For example, one method is to design the support structure of the tail to reduce deformation changes with depth, but it will affect the flexibility of the dolphin tail. Another method is to design a feed forward controller to compensate for the change of the dolphin's tail volume with depth. However, the exact relationship between depth and the tail volume change should be obtained by some experiments or modeling which is exhausted. Considering that the dorsal-ventral propulsive movement causes a periodical fluctuation in the depth, it is necessary to average the depth data within an oscillation period. The control period is set to be n times of the oscillation period.

Design of Fuzzy Controller 1

The input of fuzzy controller 1 are depth error e(k) and differential error ec(k), which are defined as:

$$e(k) = d^*(k) - d(k) \tag{5}$$

$$ec(k) = e(k) - e(k-1) \tag{6}$$

where d^*(k) is the target depth, d(k) is the measured depth and k is the sampling index. The output of fuzzy controller 1 is u_1(k). K_{e1}, K_{ec} and K_{u1}, the scaling factors of fuzzy controller 1, are defined as $K_{e1} = 1/e_{1th}$, $K_{ec} = 1/ec_{th}$, $K_{u1} = 1/u_{1th}$, where e_{1th}, ec_{th} and u_{1th} are the threshold of error, differential error and output, respectively.

Membership Function Design

Triangular membership functions with 50% overlap on neighbors are used for e, ec and u_1, as shown in Fig. 5. The input ec labeled as EC uses 5 linguistic values. The input e and the output u_1 of fuzzy controller 1, labeled as E and U_1, respectively, adopt 7 linguistic values as follows:

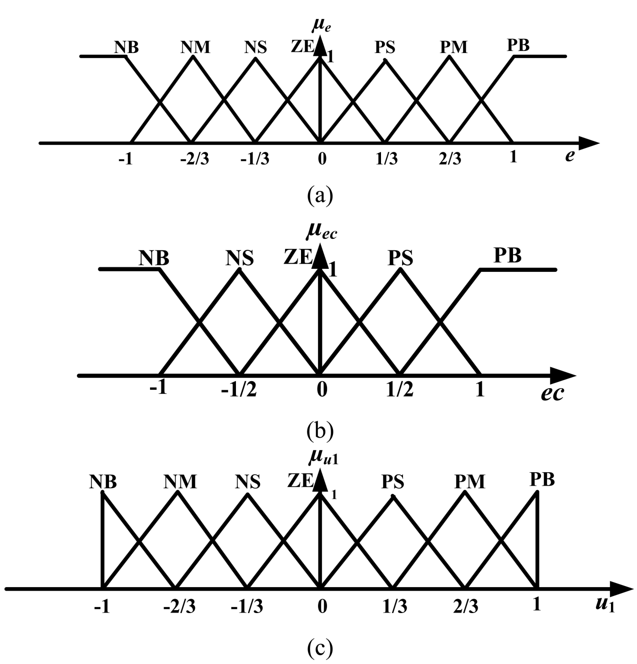

Fig. 5 (a) Membership functions for e, (b) membership functions for ec, (c) membership functions for u_1

U1	E: NB	NM	NS	ZE	PS	PM	PB
EC							
NB	NB	NB	NM	NM	NS	PS	PM
NS	NB	NB	NS	NS	ZE	PM	PB
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NB	NM	ZE	PS	PS	PB	PB
PB	NM	NS	PS	PM	PM	PB	PB

Table 1 Rule base of fuzzy controller 1

$$\begin{aligned} EC &= \{NB, NS, ZE, PS, PB\} \\ E &= \{NB, NM, NS, ZE, PS, PM, PB\} \\ U_1 &= \{NB, NM, NS, ZE, PS, PM, PB\} \end{aligned} \tag{7}$$

where NB, NM, NS, ZE, PS, PM and PB are linguistic values denoting negative large, negative middle, negative small, zero, positive small, positive middle and positive large, respectively.

Fuzzy Rule Base Design

The rule base is the core of a fuzzy controller to specify the actions that shall be taken under different situations. It reflects the intelligence of the fuzzy regulator. In this paper, the fuzzy rules are obtained from the experimental experience of the robotic dolphin pitching motion control. Each rule in the rule base has the IF-THEN form. As shown in Table 1, the rules of fuzzy controller 1 obey the following principles:

When the error is positive (negative) large and the error change is positive (negative) large, the control variable U_1 should be positive (negative) large in order to eliminate the error as quickly as possible. When the error is positive (negative) small or zero and the error change is negative (positive) large, the control variable U_1 should be negative (positive) small or negative (positive) middle to prevent overshoot.

Defuzzification

Here, the commonly used center of gravity defuzzification is adopted:

$$u_1 = \frac{\sum_{i=1}^{m} b_h \mu_{1i}(E_j, EC_k, U_{1h}, e, ec)}{\sum_{i=1}^{m} \mu_{1i}(E_j, EC_k, U_{1h}, e, ec)} \tag{8}$$

where u_1 is the defuzzification output of the fuzzy controller, m is the number of the enabled fuzzy rules in the rule base, b_h is membership function center of the fuzzy output language variable and $\mu_{1i}(E_j, EC, U_{1h}, e, ec)$ is the membership value of the ith fuzzy rule obtained according to fuzzy reasoning, which is calculated by:

$$\mu_{1i}(E_j, EC_k, U_{1h}, e, ec) = \mu_{E_j}(e) \wedge \mu_{EC_k}(ec) \wedge \mu_{U_{1h}}(u) \tag{9}$$

Design of Fuzzy Controller 2 and Intelligent Switch

Design of Fuzzy Controller 2

The input and output of fuzzy controller 2 is depth error e(k) and output u_2 that is the input of the accumulator, respectively. The membership function of u_2 is the same as that of u_1. The center of gravity method is also used to carry on the defuzzification of fuzzy controller 2. K_{e2} and K_{u2}, the input and output

	E						
	NB	NM	NS	ZE	PS	PM	PB
U2	NB	NM	NS	ZE	PS	PM	PB

Table 2 Rule base of fuzzy controller 2

scaling factors of fuzzy controller 2, are defined as $K_{e2} = 1/e_{2th}$, $K_{u2} = 1/u_{2th}$, where e_{2th} and u_{2th} are the threshold of error and output, respectively. The rules of fuzzy controller 2, shown in Table 2, obey the following principles:

When the error is positive (negative) large, the output of control variable U_2 should be positive (negative) large in order to eliminate the steady state error as quickly as possible. When the error is zero, the output of control variable U_2 should be zero.

Intelligent Switch

The intelligent switch shall be active to involve fuzzy controller 2, when necessary. When the depth error is small and this situation maintains $ic_{\max}$ control periods, fuzzy controller 2 should be active. The intelligent switch S can be expressed as follows:

$$S = \begin{cases} 0 & |e| > e_{th2} \vee 0 \le ic < ic_{\max} \\ 1 & |e| \le e_{th2} \wedge ic \ge ic_{\max} \end{cases} \quad (10)$$

where e_{th2} is the error threshold and $ic = 0$, $|e| > e_{th2}$; $= ic + 1$, $|e| \le e_{th2}$ is the small error counter. Fuzzy controller 2 is brought in when $S = 1$, and it is removed when $S = 0$.

EXPERIMENTAL RESULTS

Prototype Implementation

The prototype of the robotic dolphin is shown in Fig. 6. The shell of the head is made of glass fibre-reinforced plastic, and an air hole is drilled on the head shell to check the sealing of whole robotic dolphin. The parameters of the robotic dolphin are given in Table 3.

Experiments

To verify the rationality of the proposed controller, a series of experiments were conducted. The experiments were carried out in a pool sized 3.4 m × 2.6 m × 1.3 m (length × width × height) with the water depth of 90 cm. The robotic dolphin oscillated its tail at a frequency of 2.3 Hz to maintain the propulsion. The control period of system was about 1.79 s, 4 times the robotic dolphin's propulsion period. The parameters of controllers were given as $e_{1th} = 20$, $e_{2th} = 8$, $ec_{th} = 5$, $u_{1th} = 50$, $u_{2th} = 5$, $ic_{\max} = 5$. It is noted that the depth of robotic dolphin is about 20 cm when it is just completely submerged in the water, because the pressure sensor is installed on the bottom side of the robot's head hull.

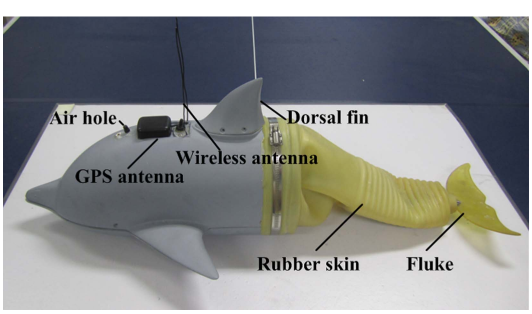

Fig. 6 The prototype of robotic dolphin

Items	Characteristics
Dimension (L × W × H)	~680 × 350 × 260 (mm)
Total mass ($m_1 + m_2$)	~9.830 kg
Mass of balance weight set (m_2)	~1.125 kg
Movement range of the balance weight (r_{amp}) (r)	50 mm
Number of the propulsive links	3
Number of the turning links	1
Length of oscillating part	~300 mm
Actuator	Servos, stepping motor
Continuous working time	~2 hours
Communication mode	Wireless (433 MHz)

Table 3 Parameters of the robotic dolphin

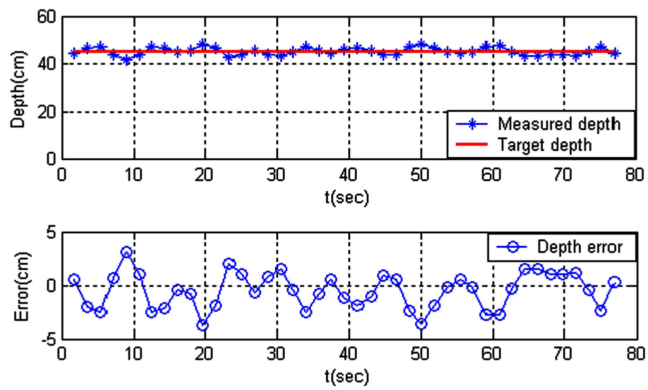

Fig. 7 Experimental result of depth control with target depth of 45 cm

In order to verify the control performance of the fuzzy PID controller, we set the target depth to be 45 cm. Figure 7 illustrates the experimental result. From Fig. 7, one can see that the actual depth of the robotic dolphin was stably maintained around the target depth and the depth error is within the range of ±5 cm. The depth error is partly caused by the periodic fluctuation of depth due to the dorsal-ventral propulsive movement, which can not be eliminated due to the measuring precision of the pressure sensor. Moreover, the water wave introduced by the movement of the robotic dolphin may also inevitably lead to the depth error. Considering all these undesirable factors, a satisfactory accuracy in depth control has been achieved.

Figure 8 demonstrates the maneuverability of the robotic dolphin, where the sequence snapshots of the robotic dolphin were recorded when the target depth was 45 cm. Since the space of the pool is limited, the robotic dolphin must be swimming in a certain turning radius to avoid running into the pool wall.

In order to further verify the proposed controller, two experiments were implemented. Figure 9a shows the experiment result of driving the robotic dolphin from water surface to the target depth of 45 cm. In the beginning, the robotic dolphin was swimming stably near water surface. When the time was 43 s, the target depth switched to 45 cm. The depth error at the moment was about 25 cm and only fuzzy controller 1 was active to compensate for the initial error. When the steady-state error was produced, fuzzy controller 2 was involved. Finally, the robotic dolphin swam stably within a small error range. There was an undershoot of the target depth because fuzzy controller 2 was involved after $ic_{\max}$ control periods, and the error is kept in a small range after the dolphin first reaches the target of 45 cm in depth. Similarly, the experiment result of robotic dolphin swimming from the target

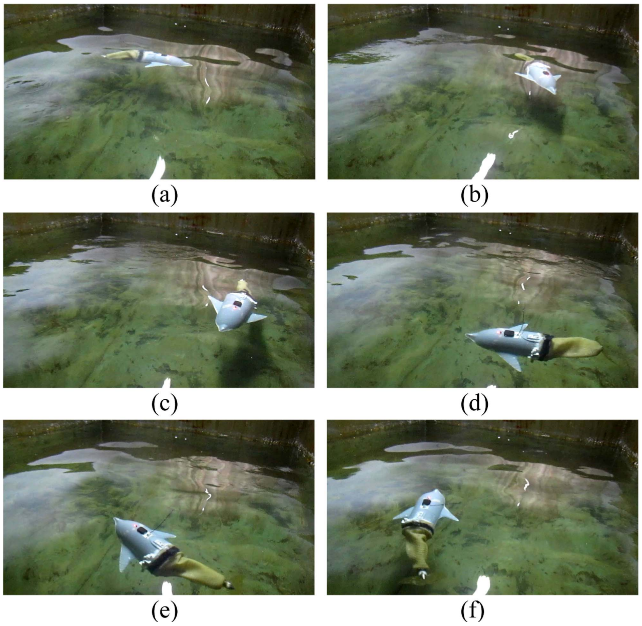

Fig. 8 Sequence snapshots of the robotic dolphin in a depth control experiment

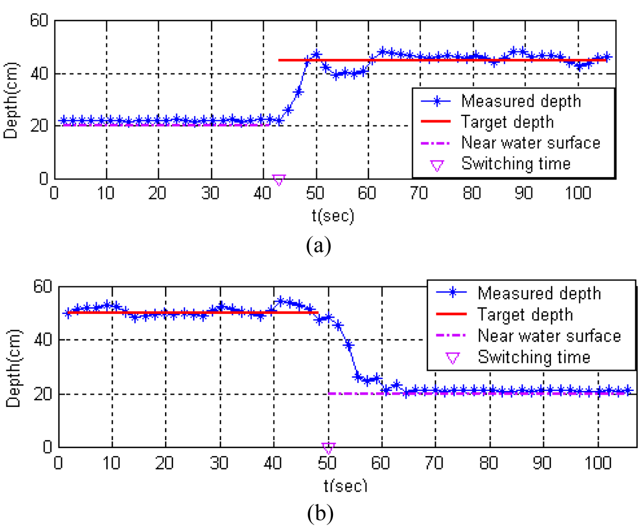

Fig. 9 Experimental results of the robotic dolphin depth control: (a) swimming from near water surface to the target depth of 45 cm, (b) swimming from the target depth of 50 cm to near water surface

depth of 50 cm to near the water surface is given in Fig. 9b. These experimental results verify the validity of the proposed fuzzy PID controller for accuracy and stability.

CONCLUSIONS

In this paper, a fuzzy PID controller for a multi-joint robotic dolphin with a barycenter adjustment mechanism is proposed to achieve depth control. The control system uses fuzzy controller 1 to compensate for initial error with fast response. Fuzzy controller 2 and the accumulator will be activated by an intelligent switch to eliminate steady-state error. The effectiveness of the proposed controller is verified by the experimental results.

In the future, the self-tuning mechanism will be introduced into the controller to further improve the control performance.

ACKNOWLEDGEMENTS

This work is partially supported by National Natural Science Foundation of China under Grants 60725309, 61105105, and 60805038. Zhiqiang Cao is the corresponding author.

REFERENCES

Dogangil, G, Ozcicek, E, and Kuzucu, A (2005). "Modeling, Simulation, and Development of a Robotic Dolphin Prototype," *IEEE Int Conf Mechatr Autom*, Canada, pp 952–957.

Fang, Z, Xu, D, and Tan, M (2011). "A Vision-based Self-tuning Fuzzy Controller for Fillet Weld Seam Tracking," *IEEE/ASME Trans Mechatr*, Vol 16, No 3, pp 540–550.

Fish, FE (2002). "Balancing Requirements for Stability and Maneuverability in Cetaceans," *Integr Comp Biol*, Vol 42, No 1, pp 85–93.

Fish, FE, and Lauder, GV (2006). "Passive and Active Flow Control by Swimming Fishes and Mammals," *Annu Rev Fluid Mech*, Vol 38, pp 193–224.

Fish, FE, and Rohr, JJ (1999). "Review of Dolphin Hydrodynamics and Swimming Performace," *Technical Report 1801*, San Diego: United State Navy.

Kumar, V, Rana, KPS, and Sinha, AK (2011). "Design, Performance, and Stability Analysis of a Formula-based Fuzzy PI Controller," *Int J Innov Comp Info Control*, Vol 7, No 7(B), pp 4291–4308.

Lauder, GV, and Madden, PGA (2006). "Learning from Fish: Kinematics and Experimental Hydrodynamics for Roboticists," *Int J Autom Comp*, Vol 3, No 4, pp 325–335.

Liu, J, Dukes, I, and Hu, H (2005). "Novel Mechatronics Design for a Robotic Fish," *Int Conf Intell Robots Syst*, Alberta, Canada, pp 807–812.

Nakashima, M, and Ono, K (2002). "Development of a Two-joint Dolphin Robot," *Neurotech Biomim Robots*, J Ayers, JL Davis, A Rudolph, Eds, Cambridge, MA: MIT Press.

Nakashima, M, Tsubaki, T, and Ono, K (2006). "Three-dimensional Movement in Water of the Dolphin Robot-Control Between Two Positions by Roll and Pitch Combination," *J Robotics Mechatr*, Vol 18, No 3, pp 347–355.

Shen, F, Wei, CM, Cao ZQ, Xu, D, Yu, J, and Zhou, C (2011). "Implementation of a Multi-link Robotic Dolphin with Two 3-DOF Flippers," *J Comput Info Syst*, Vol 7, No 7, pp 2601–2607.

Yu, J, Hu, Y, Fan, R, Wang, L, and Huo J (2007). "Mechanical Design and Motion Control of Biomimetic Robotic Dolphin," *Adv Robotics*, Vol 21, No 3–4, pp 499–513.

Yu, J, Hu, Y, Huo, J, and Wang, L (2009). "Dolphin-like Propulsive Mechanism Based on an Adjustable Scotch Yoke," *Mechan Machine Theory*, Vol 44, No 3, pp 603–614.

Yu, J, Wang, M, Tan, M, and Zhang, J (2011). "Three-dimensional Swimming," *IEEE Robotics Autom Mag*, Vol 18, No 4, pp 47–58.

Zhang, L, Zhao, W, Hu, Y, Zhang, D, and Wang, L (2007). "Development and Depth Control of Biomimetic Robotic Fish," *Int Conf Intell Robots Syst*, San Diego, CA, USA, pp 3560–3565.

Zhou, C, Cao, ZQ, Wang, S, and Tan, M (2006). "The Posture Control and 3-D Locomotion Implement of Biomimetic Robot Fish," *IEEE/RSJ Int Conf Intell Robots Syst*, Beijing, China, pp 5406–5411.