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Fuzzy Logic PID Based Control Design for a Biomimetic Underwater Vehicle with Two Undulating Long-fins

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Abstract— **This paper proposes a fuzzy logic PID based control method for a biomimetic underwater vehicle on swimming speed and yaw angle. The vehicle has a pair of long-fins installed symmetrically on its body. A set of inertial sensors are applied for collecting its velocity and pose information. And an embedded control system and a driving system based on FPGA are designed for generating and switching motion modes. Based on its motion discipline and system architecture, black-box identification is employed for system modeling. Therefore, according to the control system and driving system, a fuzzy logic PID control scheme is proposed for the underwater vehicle. A fuzzy logic controller is applied for the vehicle before the error is reduced to a given range. Then PID controller is applied when the error is within the given range. Here, velocity control is considered, which involves swimming speed and yaw angle. The fuzzy logic PID control scheme is used for the goals respectively. And Yaw angle control is prior to the swimming speed control. Finally, simulation results show the proposed control scheme is valid.**

I. INTRODUCTION

Unmanned underwater vehicle is developed greatly by the challenge of underwater robot technology to special complex environment. Fish have existed for thousands of years and supply lots of luminous ideas for underwater vehicle. It has numerous excellent features, like excellent flexibility, maneuverability etc. Therefore, biomimetic underwater vehicle (BUV) researches have become the focus of small underwater robots [1], [2], [3].

Recently, many researchers have done much of the work for BUV designs. And aiming at each BUV, a lot of control methods have been proposed. Usually, dynamic models are considered for underwater vehicles firstly. Colgate and Lynch proposed a comprehensive detailed summary about dynamic modeling and control algorithms for BUV [4]. Suzuki and Kato proposed a motion simulator based on Computational Fluid Dynamics (CFD) approach [5]. A proportional-integral-derivative control method for depth control of BUV is also proposed by Geder and Palmisano [6]. W. Zhao and L. Wang proposed a central pattern generator (CPG) control method for underwater robotic fish [7]. Saimek *et al.* proposed a maneuvering control method for a swimming machine, which decomposed the tasks into offline step of motion planning and online step of feedback tracking [8]. In addition, many classical approaches based on the waving plate and the elongated body theories etc for BUV control are also proposed [9], [10], [11]. Though researchers have done a lot on BUV, there are still some important issues which should be considered carefully. As mentioned above, most control algorithms are based on dynamic model which is built in a completely ideal fluid environment. However, in practical applications, working conditions for BUV are often not ideal; and turbulent flows exist everywhere. Another issue is that BUV control must be real-time, but most intelligent control algorithms are open-loop and very complicated. Therefore, there are a lot of works to do on BUV researches.

In this paper, a fuzzy logic PID control scheme is proposed for an underwater vehicle propelled by two symmetrical bilateral long-fins. Each long-fin is driven by ten servo motors. A set of inertial sensors are installed in its body to collect inertial information. Based on the motion disciplines of the two long-fins, the recursive weighted least squares method is employed for system modeling and parameter identification. The built model is suitable for the stable motions of the vehicle. Then, an embedded control system and a driving system are designed respectively, which provide hardware and software foundations for system control. Our control goals are swimming speed and yaw angle. Here, fuzzy logic PID control algorithms are proposed for vehicle control. For single goal control, fuzzy logic algorithm is used for reducing the error rapidly to the given range. Then PID control algorithm is used, whose control parameters are set in advance and make the error less. For lack of computational power and real-time control requirements, less fuzzy members are used in the fuzzy logic control algorithm. For the purpose of fulfilling the given control goals, yaw angle control and the speed control are applied alternately. And yaw angle control is prior to the speed control.

The remainder of the paper is organized as follows. Section II introduces the vehicle design and system modeling. Fuzzy logic PID control scheme is described in section III. Section IV presents the simulation results and relevant discussions. Finally, the conclusions and future works are given in section V.

II. UNDERWATER VEHICLE DESIGN AND MODELING

The underwater vehicle in the paper is a bio-inspired mechatronic system. The mechanism of the vehicle is introduced in this section. And the hardware and software of

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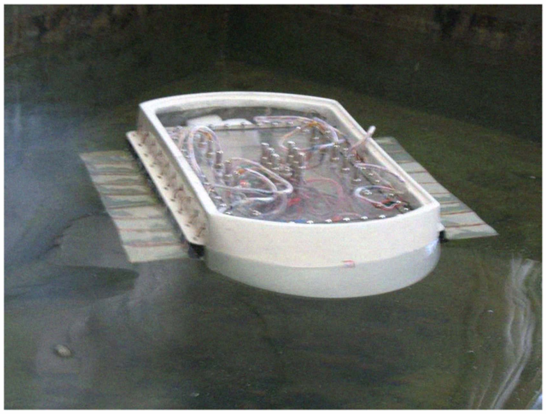

Fig. 1. The underwater vehicle

the control system are described. The modeling method is also explained in brief.

A. Underwater Vehicle Mechanism Design

The underwater vehicle is designed imitating Taeniura Lymma which is a kind of Dasyatidae fish in the Pacific. The prototype is shown by Fig. 1.

The vehicle has completely symmetrical architecture and two long-fins are fixed on both sides of the body. On each side, there are ten servo motors driving thin rigid rod (fin-ray) to oscillate. An elastic soft flat membrane is covered on the ten fin-rays. The vehicle is 817mm length, 401mm width, and 158mm height and 26kg weight.

B. Embedded control system design

Control system design for the vehicle is based on embedded system techniques. It carries out the following missions: receiving and sending command information, sensor data processing, and executing control algorithms etc, as shown by Fig. 2.

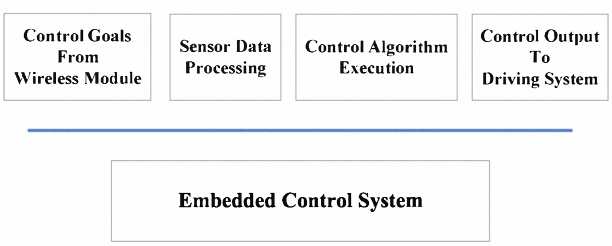

Fig. 2. Functions integration of embedded control system

In the embedded control system, a wireless radio modulator is used to receive external control commands including desired yaw angle goal and speed goal. And there are a set of inertial sensors integrated on the vehicle to collect the inertial information. A sensor data processing thread is executed to compute yaw angle and speed from the inertial information. Based on the desired goals and sensor information, the embedded control system executes relevant control algorithm, produces the control output, and sends the control output to the vehicle driving system in time.

Embedded Linux OS is used in the control system and makes the control system convenient for pipelining control.

C. Driving System Design

The driving system employs FPGA circuit to drive the servo motors of the two long-fins. There are four missions for the driving system: phase difference maintaining between adjacent ray-fins, generating PWM signals, switching motion mode, and quick-response to the top control system. for each long-fin. Like natural fish, each ray-fin of the underwater vehicle employs sine wave discipline to oscillate. Equation (1) shows the oscillating function,

$$\phi = A_{max} \sin(2\pi f t + \varphi) \quad (1)$$

Where A_{max} is the oscillating amplitude, f is the oscillating frequency, and φ is the immediate phase. And there is constant phase difference between the adjacent ray-fins. According to (1), the driving system generates relevant PWM signals for each servo motor.

Aiming at the control goals of yaw angle and swimming speed, for control convenience, two motion modes are designed which is marching mode and rotating mode. In the two swimming motion mode, each ray-fin on the long-fin has the same oscillating frequency and oscillating amplitude. And there is constant phase difference between adjacent ray-fins. The difference between marching mode and rotating mode exists in different oscillating phase for the two long-fins. In marching mode, the oscillating phase on both long-fins are same and generate equidirectional hydrodynamic force on the both vehicle sides which ensure the vehicle march steadily. And in rotating mode, the oscillation for the two long-fins is anti-phase, which generate a rotary moment on the vehicle and make it into rotating motion. Fig. 3 shows the oscillating phase of the long-fins in two motion modes.

To achieve real-time control, the embedded control system uses a SPI-like(serial peripheral interface) to communicate with driving system. The data protocol includes two parts: motion mode and control data. Therefore, a motion mode switching method is designed for control of yaw angle and speed. As mentioned above, marching mode only has effect on the vehicle speed and rotating mode does on yaw angle. Therefore, by switching motion mode, the velocity control of the vehicle may be decoupled into yaw angle control and speed control. Here, a real-time switching state

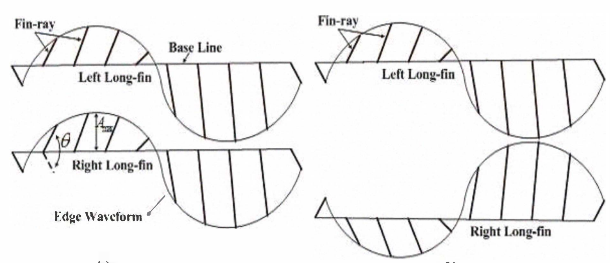

Fig. 3. Oscillating phase of the two long-fins in marching mode (a) and rotating mode (b)

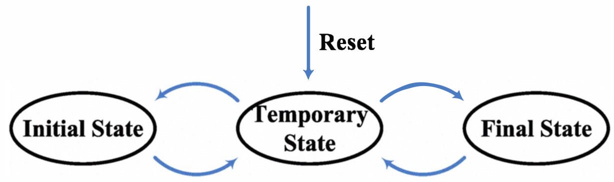

Fig. 4. Motion mode switching state machine

machine is designed. As shown by Fig. 4, a temporary state is inserted between motion mode switching. In temporary state, driving system generates signals for every servo motor which changes the two long-fins into original state as fast as possible. Then another motion mode is to start.

Finally, another function of driving system is quick-response to the top control system. Real-time response to the control command from control system is an important part for online vehicle control. Driving system based on FPGA has excellent parallel processing ability, which ensures that the control signals for each long-fin may be processed with little time delay. And this kind of fast circuit design also improves the maneuverability of the underwater vehicle.

D. Modeling

Modeling for the motion modes is based on experimental data. In marching mode and rotating mode, the servo motors on the two long-fins have completely same oscillating frequency and oscillating amplitude but different oscillating phase. According to the special oscillating discipline, modeling based on black-box identification may be achieved [12].

Modeling method uses a function as system input, expressed as

$$F_u = A\sin(2\pi ft) + \varepsilon \tag{2}$$

Where F_u is the input variable for model identification, A and f are the oscillating amplitude and frequency of servo motors respectively. ε means white noise signals for system input and its mathematical expectation is zero. Aiming at marching mode and rotating mode, speed and yaw angle are concerned respectively and defined as system output. Then the ARMA model could be achieved by the recursive weighted least squares method.

This modeling method establishes the relationship between yaw angle or speed and oscillating frequency or oscillating amplitude of the two long-fins. Therefore, it is more convenient to realize controller output for the underwater vehicle.

III. FUZZY LOGIC PID CONTROLLER DESIGN

A. Controller Scheme

Control for underwater vehicle need to be stable and realizable. For our biomimetic underwater vehicle, accurate control for swimming speed and yaw angle is difficult for two reasons. One is that the vehicle has ten ray-fins on each side and each ray-fin oscillates at sine wave discipline. From (1), there are two control variable including oscillating frequency and oscillating amplitude for each ray-fin. Therefore, too

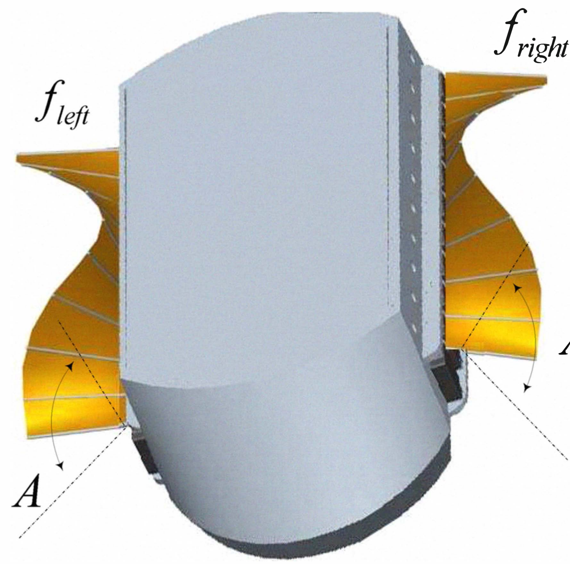

Fig. 5. Control for the two long-fin of the vehicle

many control variables make the control method difficult. The other is that non-ideal fluid environment make the model unsuitable, which may bring the control algorithm non-convergence.

In our design, oscillating frequency, oscillating amplitude and motion mode are all adjustable. Here, relevant control simplification methods are applied. For speed control, same oscillating amplitude for each ray-fin is applied and the left long-fin and right-long-fin have same oscillating phase. Therefore, the variable, control algorithms need to operate, is only oscillating frequency. For yaw angle control, same method is used but the left long-fin and right-long-fin have completely anti-phase oscillation. Fig. 5 shows how to control the two long-fins of the vehicle. To solve the second question, some control method which is independent of system model should be used to avoid non-convergence.

For velocity control including yaw angle and swimming speed, motion mode switching design of the driving system may decouple the control algorithms into mutually independent two parts. One is yaw angle control and the other is speed control. And Yaw angle control is prior to speed control. This method solved the coupling problem between the two control goals.

In this paper, a fuzzy logic PID controller scheme based on switching control is proposed for the underwater vehicle. As mentioned in section II, obviously, PID control with prepared parameters is suitable for our vehicle mostly in stable motion mode. However, the rate of convergence of PID control is fairly slow and there frequently exists nonlinearity in non-ideal fluid environment which increases instability for PID control. Therefore, fuzzy logic method is used for preliminary control. As known, suitable fuzzy members and fuzzy sets may improve the rate of convergence greatly for vehicle control. And it also may apply to some different non-ideal fluid environment. Obviously, fuzzy logic control with enough fuzzy members may achieve fairly high control resolution. But it also needs fairly strong computational power, which is difficult for the embedded control system on the vehicle. Therefore, for our underwater vehicle, a switching control scheme is designed.

Firstly, fuzzy logic control is used until the control error gets to a given range. Then PID control is switched to improve the control resolution. Fig. 6 outlines the fuzzy logic

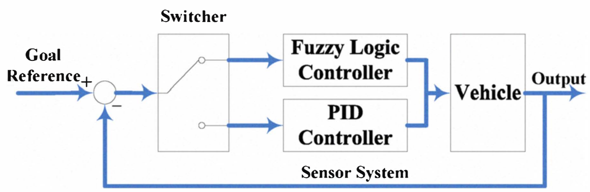

Fig. 6. Fuzzy logic PID controller scheme

PID controller scheme.

B. Fuzzy Logic Controller design

Fuzzy logic control doesn't depend on accurate system mode but human experience. For our vehicle, it is very useful for control in non-ideal fluid environment. Using speed control as an example, seven fuzzy members are set including NB (negative big), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium), and PB (positive big). And Fig. 7 shows the memberships of the members. Here, e, ec, and u accord to goal error, goal error change, and controller output, whose fuzzy sets are different respectively. As known, the membership function determines weighting of the seven fuzzy sets that contribute to the control input for the two long-fins. When the vehicle swims much slower than the desired speed, the maximum controller output is used for the long-fins. Similarly, if the vehicle swims much faster than desired speed, the maximum negative controller output for the long-fins. For avoiding large control overshoot, controller output becomes fairly small when the error is near the given range. Table I shows the control rule table.

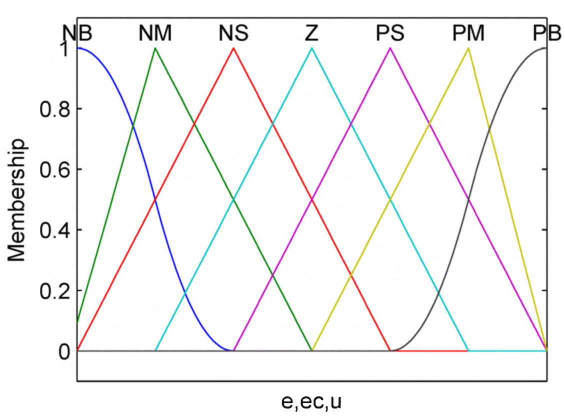

Fig. 7. Membership in fuzzy logic control

TABLE I

CONTROL RULE TABLE

u		ec						
		NB	NM	NS	Z	PS	PM	PB
	NB	PB	PB	PB	PM	PS	Z	Z
	NM	PB	PB	PM	PS	Z	Z	Z
	NS	PB	PM	PS	Z	Z	Z	NS
e	Z	PM	PS	Z	Z	Z	NS	NM
	PS	PS	Z	Z	Z	NS	NM	NB
	PM	Z	Z	Z	NS	NM	NB	NB
	PB	Z	Z	NS	NM	NB	NB	NB

In addition, different to speed control, anti-phase controller outputs are used for yaw angle control for the left long-fin and right long-fin. The control rules are same with speed control.

C. PID Controller Design

Prepared PID control parameters ensure that classical PID control techniques can apply to the vehicle for further control. Take speed control for example, PID control algorithm can be expressed as,

$$u = K_p e + K_i \int e + K_d ec \qquad (3)$$

Where, u is the controller output, K_p is the proportional gain, K_i is the integral gain, K_d is the derivative gain, e is the speed error, and ec is the speed error change. In stable motion mode, the model for the vehicle is fairly accurate. Therefore, relevant PID parameters including K_p, K_i, and K_d may be achieved off-line.

When the error controlled by fuzzy logic control algorithm gets to a given range. PID control is switched for further control. With excellent control parameters, PID control has fairly high control resolution and this method is also very convenient for online embedded computer control.

D. Velocity Control for The Vehicle

Velocity control including yaw angle and swimming speed is very important for point-to-point trajectory control. As mentioned above, speed control and yaw angle control can be decoupled by switching control goals.

When the vehicle is in swimming mode, yaw angle is observed all along. Once the yaw angle changes from the desired goal, fuzzy logic PID control algorithms for yaw angle are executed. And the driving system switches the marching motion mode into rotating motion mode until

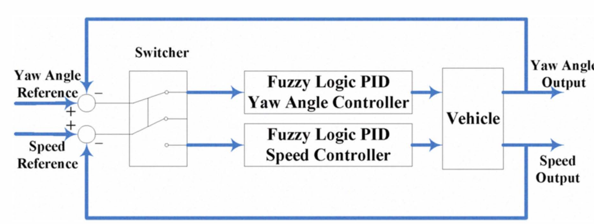

Fig. 8. Velocity control for the vehicle

the yaw angle satisfies the desired yaw angle. Next step, fuzzy logic PID control algorithms for speed are executed. And driving system switches the rotating motion mode into marching motion mode until the speed satisfies the desired value. Fig. 8 outlines the velocity control scheme.

In rotating motion mode of the underwater vehicle, generated hydrodynamic force only affect the yaw angle and doesn't do on speed of the vehicle. And the control signals for the two long-fins are also synchronous, which ensures that the speed control and yaw angle control may be separated completely.

IV. SIMULATION RESULTS

Firstly, swimming speed control based on fuzzy logic PID algorithms is tested. Based on the marching model shown by (4), PID control parameters are chosen in advance. Let set the speed goal as 0.4 m/s. Fig. 9 shows the predictable simulation result.

$$v = 10^{-4} * F_u * \frac{2.425z^{-1} + 3.683z^{-2} + 4.762z^{-3}}{1 - 1.871z^{-1} + 1.030z^{-2} - 1.059z^{-3}} \quad (4)$$

In Fig. 9, the given switching range is set as -0.3 m/s∼0.3 m/s. And when the error is less than 0.1 m/s, PID control algorithm is switched to replace fuzzy logic control algorithm. From (1), the controller output is F_u and the two long-fins have totally same controller output signals for speed control. Fig. 10 shows the controller output on the two long-fins.

Secondly, yaw angle control is tested and the rotating model is shown by (5), where θ accords to yaw angle of the vehicle.

$$\theta = F_u * \frac{5.950z^{-1} - 8.578z^{-2} + 4.884z^{-3}}{1 - 1.015z^{-1} + 0.492z^{-2} - 0.497z^{-3} + 0.004z^{-4}} \quad (5)$$

Same as speed control, 100° is set as desired yaw angle. And Fig. 11 and Fig. 12 show the simulation result and controller output on the two long-fins. In Fig. 12, opposite controller output on the two long-fins mean that the oscillation is completely anti-phase for the two long-fins. Because the model is built by online parameter identification method and there exists some influence factor like mass center disproportion and servo motor driving force difference etc,

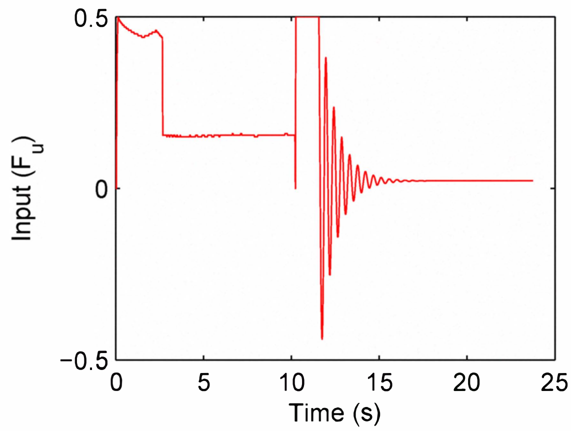

Fig. 10. Controller output for the two long-fins in speed control

there are certain deviation on the two long-fins.

Finally, velocity control including yaw angle control and speed control based on switching fuzzy logic PID control algorithm is simulated. The desired swimming speed and desired yaw angle are 0.6m/s and 60° respectively. Fig. 13 - 14 shows the simulation results. Control error for the vehicle are shown by Fig. 15.

Fig. 13 shows that control algorithms are separated into two parts. Speed control program is not executed until the yaw angle satisfies the desired value. And for each control part, fuzzy logic control and PID control are executed respectively. With the well-chosen PID parameters, the control results of the second part are excellent. In addition, Fig. 15 shows that there are little overshoot and little stead state error, which ensures velocity control for the vehicle has high stability.

Three parts of simulations show our control scheme for the vehicle is valid. Vehicle response to speed and yaw angle control based on fuzzy logic PID method displays a smooth transition to steady state. And the error of PID control in second stage satisfies the control demands. Compared with traditional underwater vehicles, our biomimetic vehicle has

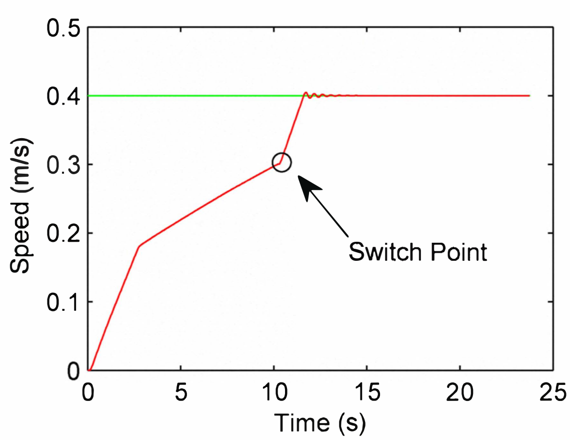

Fig. 9. Speed control based on fuzzy logic PID control

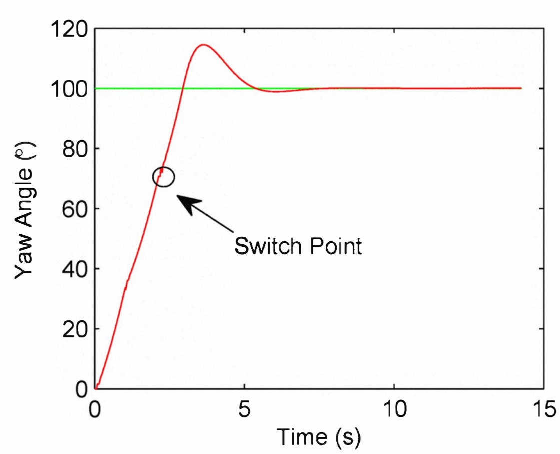

Fig. 11. Yaw angle control based on fuzzy logic PID control

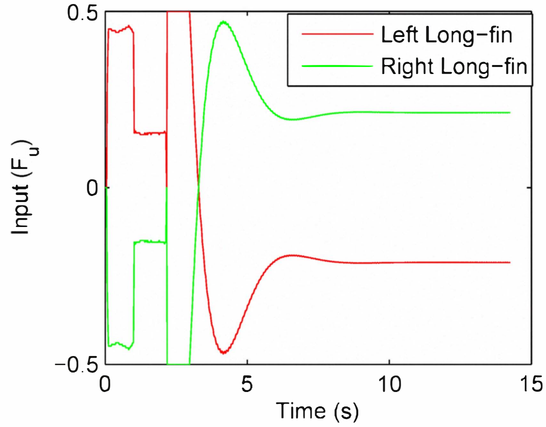

Fig. 12. Controller output for the two long-fins in yaw angle control

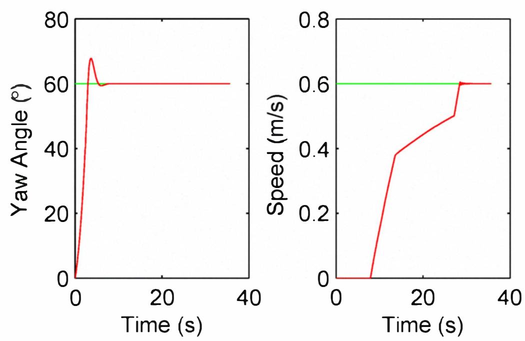

Fig. 13. Velocity control for the vehicle

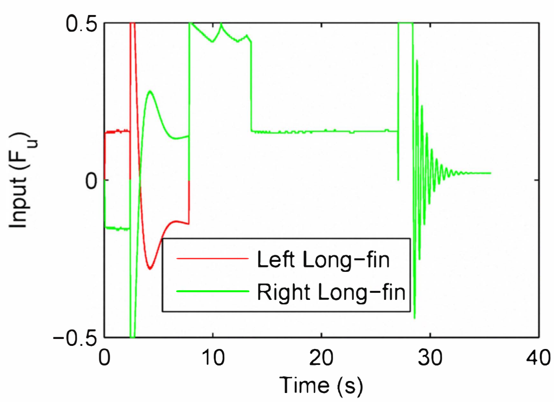

Fig. 14. Controller output for the two long-fins in velocity control

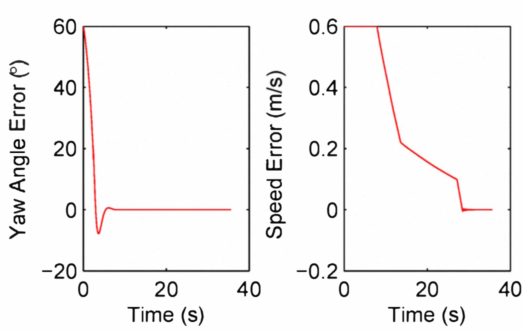

Fig. 15. Error in velocity control

complex driving method. And the presented control scheme is suitable for velocity control. It also decreases the inertial influence brought by large weight and high speed.

V. CONCLUSIONS AND FUTURE WORKS

A prototype vehicle to demonstrate the propulsion performance of its two controlled long-fins is developed. Based on the control system design and driving system design, fuzzy logic PID based control scheme is proposed to control the swimming speed or the yaw angle control for the vehicle. In consideration of non-ideal fluid environment and rapid convergence, fuzzy logic control algorithm is executed first. Then PID control program with excellent well-chosen parameters is executed for further accurate control. For velocity control, control scheme is decoupled into two parts: yaw angle control and speed control. And yaw angle control is prior to speed control. Finally, Simulation results show the methods are valid.

Future works will focus on the experimental verification. Actual experiments on the vehicle would be carried out in different fluid environment, which are used to verify relevant control algorithms and supply new scheme for more complex trajectory following.

VI. ACKNOWLEDGMENTS

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