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Fuzzy PID Algorithm-based Motion Control for the Spherical Amphibious Robot

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***Abstract* – Fuzzy control and PID control are often used in control area. However, a single Fuzzy control or PID control can not satisfy the need of the rising complexity and precision of control systems. Considering the disturbance in amphibious spherical robot, it is difficult to solve the control problem for a complex system of an amphibious spherical robot. This paper deeply analyzed the advantages and the disadvantages of Fuzzy control and PID control, and proposed a new Fuzzy PID control combined Fuzzy control and PID control. The simulation results show that the method of Fuzzy PID can effectively reduce the overshoot of the control system, accelerate the response speed, and shorten the adjustment time, In this way, The system can reduce the shock of amphibious spherical robot, and improve the stability, thus, the method can enhance the dynamic performance of the amphibious spherical robot.**

Index Terms* – *Amphibious spherical robot, Fuzzy PID control, PID control, Dynamic performance

I. Introduction

Researches of the amphibious spherical robots have been focused on by researchers around the world. With a high adaptive faculty, amphibious spherical robots can be used in broad applications including pipeline cleaning, submarine topography survey, samples collection, topography surveys, water-quality monitoring, sample collection, and recovering objects on land and underwater.

Snake-like robot is developed by Tokyo university of science and technology, it is equipped with cameras in head, can be used to seek in the ruins of the disaster victims, especially in earthquake-prone countries such as Japan, the robot is very useful [1]. In 2010, The institute of electrical and electronic engineering at the university of Manchester, started to make the research of amphibious spherical robot. S.Watson and P.N.Green develop a tiny autonomous underwater robot MKV. The sphere diameter of autonomous underwater robot is 0.15 meters, the propulsion system use six propeller, MKV has four degrees of freedom of movement [2]-[4]. Hawaii University has been developed a spherical underwater robot: Omni-Directional Intelligent Navigator, This spherical robot is mainly used for monitoring the water environment and underwater operations. The air quality is about 126 kg. There are eight propeller in robot, the robot with sonar sensors, pressure sensors and inertial navigation system [5] [6].

The amphibious spherical robot has been a useful tool in our daily life, the way to realize the control is the key to research robot. The problem of how to control the amphibious robot is related to many aspects. The most difficult point is mainly about the circumstance, where a great number of disturbances exist. The effects of various kinds of turbulence and uncertain factors are add to the difficulty of amphibious spherical robot control [7]-[9]. The resultant performance cannot satisfy our requirements when using some traditional methods to design the controller of amphibious spherical robot.

Traditional PID control is mainly control the model of the linear process, and, in fact, most industrial processes are exist in different degrees of nonlinear, sometimes even very serious nonlinear, some process is difficult or can not be established mathematical model, at the same time, the general PID control can not achieve precise control for such process, However, Fuzzy control does not need to establish the mathematical model, the Fuzzy control is suitable for the complex robot, which is difficult to establish accurate mathematical model. It is the main cause that it always used in industrial process control, Fuzzy control get more and more widely use. Of course, it is difficult using traditional PID for the amphibious spherical robots. Because the overshoot of the traditional PID is bigger than other methods. When confronted with the interference from the outside world, it has a poor stability.

Fuzzy control system is a typical intelligent control system, The computer and people describes control activity with natural language, it can achieve good control do not need to know the mathematical model of control object, There are many benefits. It use fuzzy set theory as the control principle, Using mode paste language variables, fuzzy logic reasoning knowledge and fuzzy thinking method to control the complex process. However the Fuzzy control system does not have too many differences with the traditional PID control system, the main difference is Fuzzy control with intelligent fuzzy controller. The fuzzy controller is the core of the fuzzy control system. Fuzzy controller mainly includes input blurred, knowledge base reasoning, decision-making, and output accurate four parts. The performance of a fuzzy control system mainly depends on the structure of fuzzy control, the fuzzy rules adopted, synthesis reasoning algorithm and fuzzy decision method and other factors. But the fuzzy control has a long training time, which could not accepted by most control system. So it is necessary to combine Fuzzy control with PID control. The Fuzzy PID control is based on the traditional PID control and the fuzzy set theory. It has the fast response speed, small overshoot and short transition time, etc. For the amphibious spherical robot, when the overshoot is small, it is mean the amphibious spherical robot has a great stability. In addition, the amphibious spherical robot will has a precise trajectory tracking when the time of adjust is short. So it is obviously the Fuzzy PID is more suitable for the real control law of the amphibious spherical robot.

The paper introduces controller combined with Fuzzy and PID control to deal with the motion control of the amphibious spherical robot. The effectiveness of the Fuzzy PID controller is verified by simulation results.

The paper is organized as follows. Some research about amphibious robots is introduced in section I. In section II, the structure of amphibious spherical robot is described. Section III introduces the Fuzzy PID controller. In section IV, the simulation results of both simple PID control and Fuzzy PID control are present. Finally, in Section V, presents conclusions and future work.

II. Structure of Amphibious Spherical Robot

The amphibious spherical robot can walk on land and move under the water. An amphibious spherical robot can realize more degrees of freedom movement with actuator units, the work to analysis and control a system is to construct the mathematics model, which is an important method and precondition. If we want to realize underwater robot motion control precisely, it is necessary to know its model precisely.

A. General Design

The amphibious spherical robot is shown as in Fig. 1. The amphibious robot consists of a sealed transparent upper hemispheroid, two transparent quarter spherical shells that can be opened and four actuating units. Each unit consists of a water-jet propeller and two servo motors [10]-[12]. They are perpendicular. The control circuits, power supply, and sensors are placed in the sealed upper hemispheroid, which is waterproof. The amphibious spherical robot can float up and float down depends on water-jet propeller. In addition, we can change the speed of the robot by adjusting the propeller thrust. The design of the amphibious spherical robot is shown in Fig. 1. The robot has two actuating modes: quadruped walking mode and water-jet propulsion mode.

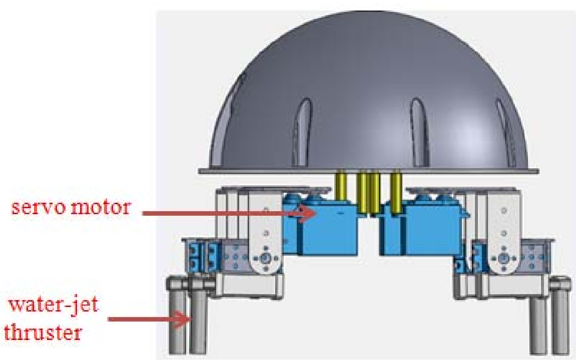

Fig. 1 Structure of amphibious spherical robot

B. Actuating System

As shown in Fig.2, The amphibious spherical robot has four actuating units. Each unit contains one water-jet motor, two servo motors and a water jet thrusters made of stainless steel. The movement of the amphibious spherical robot is realized by four water jet thrusters. The motor is controlled to move with the PWM signals. The servo motor can rotate 180°. At the same time, another motor fixed on the water-jet thruster is controlled to move in vertical direction [13],[14]. Two degrees of freedom movement can be implemented by each actuating unit with using servo motors. And eight servo motors control the rotations of these thrusters. As the amphibious spherical robot walk on land, actuating units are used as legs, each of which has two degrees of freedom. Four driving leg constitutes the quadruped robot. The robot can realize walking and rotating motions on land by adjusting the PWM signals. And the amphibious spherical robot can move due to water jet propellers under the water, producing thrust can make the robot move. By controlling PWM signals of the servo motors, spray angle of each water- jet propeller can be altered to implement multi-degree freedom such as moving forward, rotating, floating up and floating down motions.

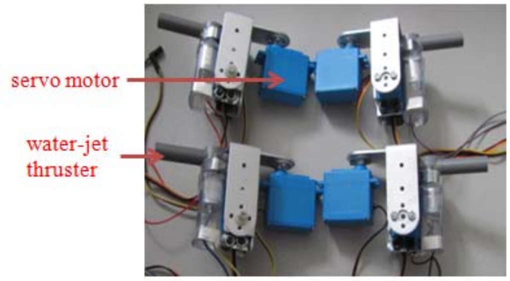

Fig.2 The water-jet thruster

C. Description of Motion and Control System

On land, the amphibious spherical robot can implement walking. The horizontal servomotor actuates the water-jet propeller to swing forward. The water-jet propeller is swings forward and backward to complete walk on land. The spherical robot can walk with different velocities by changing the PWM signals.

The block diagram of the control system for amphibious spherical robot is shown as in Fig. 3. And the prototype control system is show in Fig.4. An AVR micro unit is used as the CPU of the system for amphibious spherical robot, which generates PWM signal to control servo motors and water-jet motors with the four actuating units. In addition, it can change the state of the amphibious spherical robot. In order to adapt to underwater environment, It is also generates PWM signal to control the four water-jet motors. By adjusting the PWM signal, we can change both the direction and the size of water-jet thruster [15]-[17].

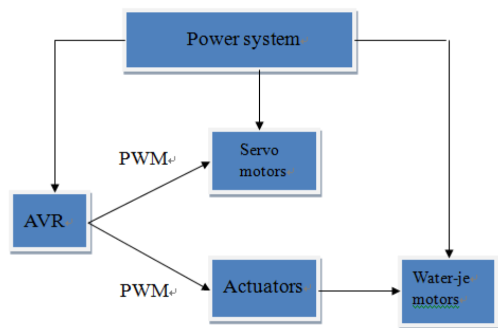

Fig. 3 Block diagram of the control system

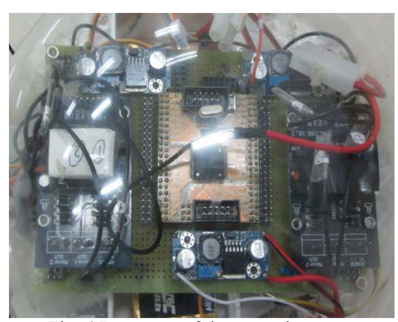

Fig. 4 Prototype of the control system

Fig.5 shows the prototype of the amphibious spherical robot, which includes two quarter spherical hulls, four actuating legs and one circular acrylic plate. Waterproof work is an essential to realize the underwater motion. When the amphibious spherical robot walks on land, nozzle of water-jet propeller is used as the amphibious spherical robot's leg.

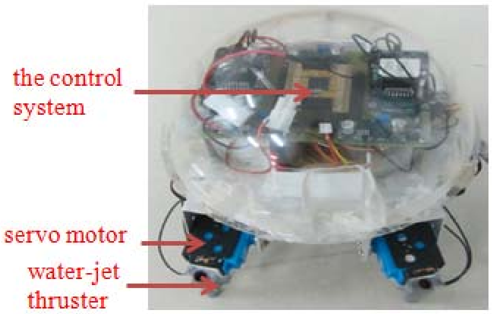

Fig.5 The prototype of amphibious spherical robot

III. CONTROL ALGORITHM FOR THE AMPHIBIOUS SPHERICAL ROBOT

A.PID Control

With the rapid development of science and technology, The demand of control accuracy, response speed of automatic control system and stability of the system is higher, traditional PID control is mainly control the model of the linear process truly, and, in fact, most industrial processes are exist in different degrees of nonlinear, some process is difficult or can not established mathematical model at the same time, So the general PID control can not achieve precise control of such processes.

Classic PID control has been widely used because of its simple construction and good robustness. In project practice PID control still take the dominated place. The principle of PID control is to constitute a control with proportion, integration and differential, then choosing proper linear combination in order to control the target. As shown in Fig.6.

The feature of PID control is only change the controller parameters, can obtain satisfactory results. PID controller is a linear controller. For the control equation:

$$e(t) = x(t) - y(t) \tag{1}$$

The control law for PID controller is:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dt} \tag{2}$$

Where k_p is proportion gain coefficient, k_i is integration time coefficient, k_d is differential time coefficient.

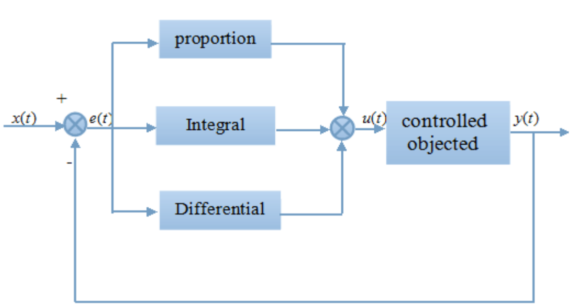

Fig.6 Schematic of a PID controller

B. Fuzzy control

Basic fuzzy control system including fuzzing, fuzzy reasoning and processing narrated. The basic structure of fuzzy control system is shown in Fig.7.

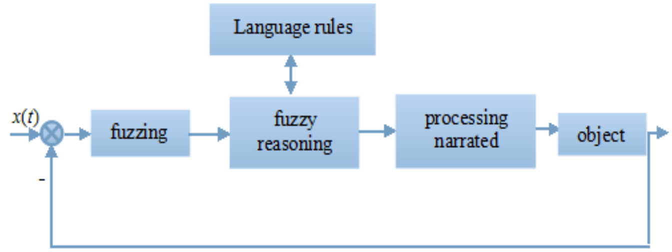

Fig. 7 Block diagram of Fuzzy control system

The processing of Fuzzy controller is to determine the value of the input in the process, at the same time, change the corresponding values of fuzzy language variables, the values of corresponding language variable are defined by the corresponding membership degree. Through such a theory that the input variables are mapped to the domain range with appropriate response process, accurate input data will transform into the appropriate language value or fuzzy set identifier. The general fuzzy controller uses the error and the error change as the input language variable.

Fuzzy reasoning commonly adopt the conditional sentences such as IF A THEN B to describe, including three parts: the major premise and minor premise and the conclusion. Major premise is multidimensional fuzzy conditional statements, which constitute a rule base, Adjustment and calibration of fuzzy rules is a key problem in fuzzy control [18]-[20].

Processing narrated is an important part of the fuzzy system, fuzzy reasoning is converted the fuzzy quantity into precise value. Common methods of the processing narrated have the maximum membership degree method, area average method, gravity method and maximum transferred to the average degree method.

Fuzzy control is the process of the interaction between these three links, it is key part is to choose suitable fuzzy membership function, use the reasonable reasoning method to come to a conclusion and adopt the appropriate methods of clear to restore the accurate quantity.

C. Fuzzy PID control

The structure of the Fuzzy PID control is mainly composed of the system of PID that the parameters can be changed online and the fuzzy control system. Fuzzy reasoning system make error e and error change rate ec as the input. Adjust the parameters of PID by using the fuzzy reasoning method to meet the different requirements of the Fuzzy PID control when sent different error e and error change rate ec. And make the controlled object has a good performance of the dynamic and static state. Fuzzy PID controller with error e and error change rate ec as input, PID parameter k_p k_i k_d as output, error e and error change rate ec can satisfy the self-tuning of the PID parameters. Using the fuzzy control rules to modify the PID parameters online, where we constitute a Fuzzy PID controller, the structure is shown in Fig. 8.

Fuzzy PID control not only have the simple structure and strong robustness of the traditional PID control system, but also have a better control precision. At the same time, the control of Fuzzy PID controller is more flexible.

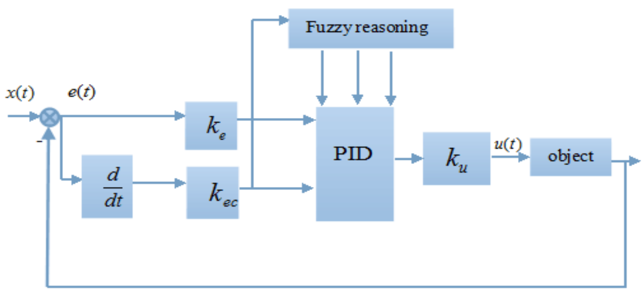

Fig.8 Block diagram of Fuzzy PID control system

Where e is error and ec is error change rate, so k_e and k_{ec} are quantitative factors. k_u is the scaling factor.

Make the system deviation e and deviation rate ec as the Input language variable of fuzzy PID controller, k_p, k_i, k_d are the output variable language. Their range is defined as a basic theory of fuzzy set .

$$e, ec, k_p, k_i, k_d = (-4,-3,-2,-1,0,1,2,3,4)$$

The fuzzy subset is:

$$e, ec = \{NB, NS, ZE, PS, PB\}$$

The meaning of the subset elements are: negative large, negative small, zero, large, small.

The membership functions of fuzzy state generally choose the method of symmetric triangular, Symmetric trapezium and Normal type. Because the shape of triangle membership function is only related with its straight slope, the operation is simple, and the occupied memory space is small, therefore the method of symmetric triangular more suitable for the Fuzzy PID control of adjust membership function online. So we choose the method of symmetric triangular as the membership function of the language variable. As shown in Fig 9.

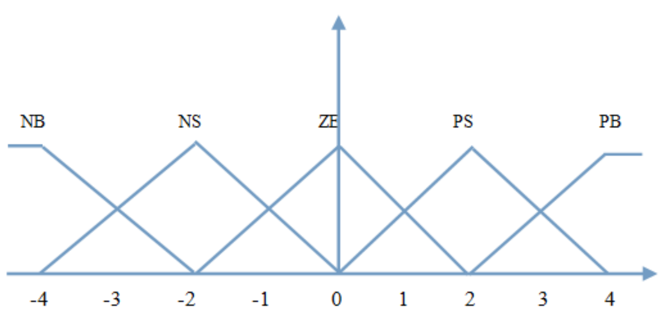

Fig. 9 diagram of the symmetric triangular membership function

In fact, the impact of the shape of the membership function (triangle, trapezoid or normal distribution, etc.) on the control is not large, The impact of the size of each son fuzzy sets is big, generally speaking, if appropriate, the effect in width of each fuzzy subset control will different, if the width is small, selected parts do not have rules, so the convergence is bad, on the contrary, If there have the overlapping rules, the mutual influence between rules make the response slow. Therefore, e and ec adopting same membership function, at the same time k_p, k_i, k_d also use the same membership function. In order to determine e, ec and the membership assignment table of k_p, k_i, k_d.

The control rule is the core of Fuzzy PID controller. According to experience and perception reasoning and a large number of successful control strategy in daily life, We use input and output variables to describe fuzzy state, get the control rules. Therefore, develop a Fuzzy PID control rules as follow:

(1) When starting or stopping running motors, the output of the motor's speed deviation e is big, to accelerate the response speed, can improve the value of k_p, At the same time, in order to avoid the differential supersaturated, the k_d take medium, In order to prevent the overshoot of the motor's speed is over large, We usually remove the integral action, so $k_i = 0$.

(2) When the motors of the amphibious spherical robot at normal speed, deviation e and deviation rate ec in medium size, in order to make the rotation speed of the motors has a small overshoot, k_p should take smaller; the values of k_i take medium, the value of k_d is take large, In this way, the influence to the performance of the amphibious spherical robot is good, and we also can ensure the response speed of the robot.

(3) When the speed of motors is keep constant, and the error e is small, to make the stable performance of the robot is good, should increase k_p and k_i, at the same time, To avoid oscillation phenomenon in the amphibious spherical robot near the set value, and improve an anti-interference performance of the robot, the value of k_d is quite important. Generally if ec is lesser, k_d get larger, and ec is larger, k_d get smaller.

According to above analysis can make a Fuzzy PID control rules as shown in table 1.

TABLE I

Fuzzy PID inference rules of k_p k_i k_d

ec \ e	NB	NS	ZE	PS	PB
NB	PB NB PS	PB NB ZE	PB NB ZB	PB NB ZE	ZE ZE PS
NS	PB NB NB	PS NS NB	PS NS NS	ZE ZE ZE	NB ZE PS
ZE	PS NS NB	PS NS NB	ZE ZE NS	NS PS ZE	NB PS PS
PS	PS NS NB	ZE ZE NS	NS PS NS	NS PS ZE	NB PB PS
PB	ZE ZE PS	NS PS ZE	NS PS ZE	NB PB ZE	NB PB PS

The output parameters of the Fuzzy PID controller are expressed as below:

$$k_p' = \frac{k_p - k_{p\min}}{k_{p\max} - k_{p\min}} \quad (3)$$

$$k_i' = \frac{k_i - k_{i\min}}{k_{i\max} - k_{i\min}} \quad (4)$$

$$k_d' = \frac{k_d - k_{d\min}}{k_{d\max} - k_{d\min}} \quad (5)$$

The result of fuzzy reasoning, namely the output variables of Fuzzy PID controller, is a fuzzy set, can not be directly used to control the object, need to be converted into accurate quantity that actuator can be performed. The process is generally referred to as the solution of fuzzy. The method is center of gravity, this method used in Fuzzy PID control system more widely.

$$z^* = \frac{\int_a^b z\mu_c(z)dz}{\int_a^b \mu_c(z)dz} \qquad U = [a,b] \tag{6}$$

Where z^* is the center of the membership function $\mu_c(z)$ of the fuzzy sets. After look up table, we can get the value of k_p, k_i, k_d .then we can through type (3) ~ type (5) obtain three self-tuning parameters.

IV. Simulation and Results

The simulation is carried out in this paper to verify the proposed method. We mainly pay attention to the control of the amphibious robot in water. Hydrodynamic forces and moments are one of the main causes of damping. We can express the hydrodynamic forces and moments in Eq.

$$M\dot{v} + (D(v))v + g(\theta) = \tau$$

Where M is rigid body mass matrix, $(D(v))v$ is the damping term, $g(\theta)$ is the resilience and torque vector, θ is position vector, v is velocity vector and τ is control vector.

To describe the position, linear and velocities of the amphibious robot, we bring the numerical value to the formula, the transfer function is:

$$G(s) = \frac{1}{61.84s^2 + 6.128s + 3.265} \tag{7}$$

A. Establish the frame diagram of control system

Design the figure of the system in the environment of Simulink of MATLAB, as shown in Fig 10.

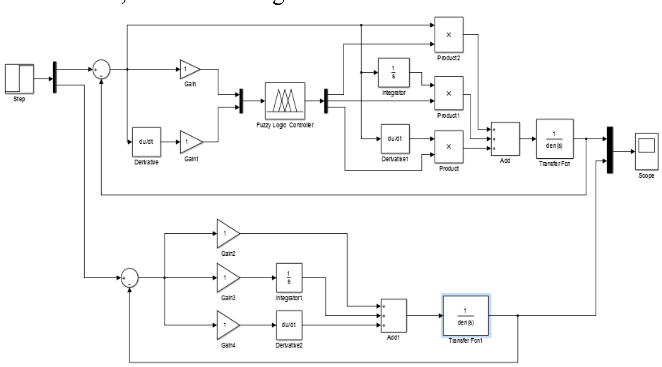

Fig .10 the simulation frame diagram of control system

B. The analysis results of simulation

Where the error and the error rate are $k_e = k_{ec} = 0.01$ .and The initial value of k_i, k_p, k_d are $k_i = 1.35$, $k_p = 2.5$ and $k_d = 1.7$ .The cycle of the Collect sample is $T = 0.02s$ .The Step input is $R = 1.0$.

The graph of the regular PID control and Fuzzy PID control with Step input as shown in Fig.11.

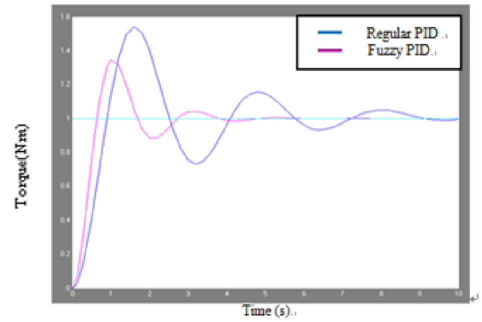

Fig .11 the graph of the regular PID control and Fuzzy PID control with Step input

The color of the Fuzzy PID is read and the regular PID is blue, the step input and the output response of the control model are shown in the diagram. It can be seen that the maximum overshoot output of the regular PID is 48.5%, at the same time the maximum overshoot output of the Fuzzy PID is 37.2%. The time of adjust of the regular PID control is 9s, and the time of adjust of the Fuzzy PID control is 5s, It is obviously that the time of adjust of Fuzzy PID control is shorter than regular PID control, And the transition of the Fuzzy PID control is smooth .Will follow the value of the input better. And it has a high precision of the control and small amount of overshoot, the rise time of the Fuzzy PID control is shorter than regular PID control, that is mean the Fuzzy PID control has a better response speed. So the effect of the Fuzzy PID control is better.

In order to further understand the performance of the control system, we have the input with a sinusoidal variation, when the signal is a sine wave signal. Results are shown in Fig 12.

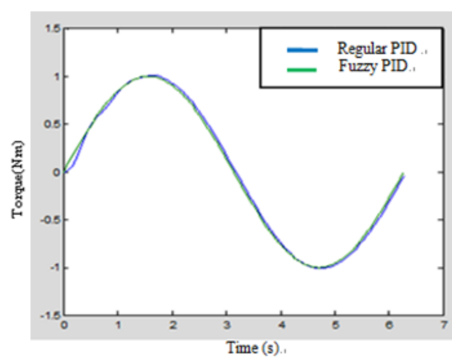

Fig .12 the graph of the regular PID control and Fuzzy PID control with sine input

The color of the Fuzzy PID is green and the regular PID is blue, compared with the Fuzzy PID control and Regular PID control, and the output of the Fuzzy PID control system can track the standard input more accurate, quick and smooth, which shows that the performance of the Fuzzy PID control is better.

Through the simulation and experiment, it can be seen that the Fuzzy PID adaptive control can effectively overcome the influence of load disturbance, and the algorithm is relatively simple, and it has a small amount of calculation, so The Fuzzy PID control is a kind of practical and pretty control strategy.

We can see, the amphibious spherical robot is tracking the ideal output very well when we take the Fuzzy PID control, In addition, the Fuzzy PID controller has high accuracy and reliable stability for the amphibious spherical robot. Because it has a small amount of overshoot and a fast response speed.

V. Conclusions and Future Work

This paper presented the design of control system of the amphibious spherical robot using the Fuzzy PID controller, which had a lot of great superiority for the amphibious spherical robot. Compared with simple PID control or Fuzzy control, the controller which combined PID and Fuzzy had a better performance, including a small amount of overshoot and a fast response speed. Of course, the time of adjust is short.

Compared with the PID control, Fuzzy PID control algorithm has better performance. It has the obvious effect in Shorting the transition time. three parameters k_p, k_i, k_d selected by Fuzzy PID control system are always changed, more in line with the control rules of the object, and has a certain law of nature, namely the parameters of the controlled object model always changed, But the Fuzzy PID controller is still have a better ability of control.

At the same time, the controller combines PID and other methods, such as neutral network control will be considered in future work.

Acknowledgment

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