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Design of Fuzzy Adaptive PID Temperature Controller Based on FPGA

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Abstract

Aiming at the characteristics of a certain thermostat control system such as non-linear and time varying, combining the traditional PID controller with modern fuzzy control theory, and using the EP1C12 FPGA as the core controller, the fuzzy adaptive PID temperature controller is going to be designed and achieved. The deviation and deviation rate are the inputs of fuzzy PID controller. PID parameters are the outputs of fuzzy PID controller. A set of fuzzy rules is used to achieve the online optimal regulation for the PID parameters. The simulation results of the system show that this method can significantly improve the control effect. With the simplification of the design, the computational speed and reliability of the system are also improved.

***Key words**: FPGA, temperature control, fuzzy adaptive PID control*

1. Introduction

Temperature is one of the main controlled parameters in the process of industrial production. At present, the conventional PID controller is often used for temperature control. PID controller has some advantages, which are simple in structure and easy to realize. It has good control effect for the steady system that can build an accurate mathematical model. But due to the complexity of actual temperature control system, varied parameters, large inertia and large delay, the conventional PID controller is difficult to control their high precision. Fuzzy control has strong robustness. It doesn't need the precise mathematical model of the controlled object, and only depends on the experience, knowledge and manipulate data of operators. It is suit for controlling Nonlinear Time-Varying delays system. Because of the poor static performance, the applied range is limited. To solve these problems, a fuzzy adaptive PID temperature controller that based on FPGA is designed. This program combines the traditional PID control with modern fuzzy control. Using the fuzzy reasoning methods is to achieve the auto-tuning PID parameters. Fuzzy control is an important branch of intelligent control. It is mainly to imitate human control experience rather than rely on the mathematical model of the controlled object. If combining the fuzzy control with PID control and making it into the fuzzy adaptive PID controller, the PID parameters will not rely on the mathematical model of the controlled object, and they can be adjusted dynamically in order to be optimal[1-2]. Thus, according to the MATLAB Simulation results, the control algorithm is proved to be feasible. And applied it to the temperature control of the incubator, the performance [3] of the controller for incubator control system is obviously superior to the traditional PID controller [4-8].

2. The Fuzzy Adaptive PID Control Principle and Structure

2.1 The Principle of Fuzzy Control

Fuzzy control uses the control algorithm that based on fuzzy sets, fuzzy prediction and fuzzy logic, and it uses the Fuzzy mathematics to achieve the nonlinear intelligent control. It applies the knowledge base, which was made of human's practical experience, to control the object. At this point, control input is not a certain amount, but a fuzzy relationship. The output can be an accurate value after doing the defuzzification. The schematic diagram of Fuzzy control principle is shown in Figure 1.

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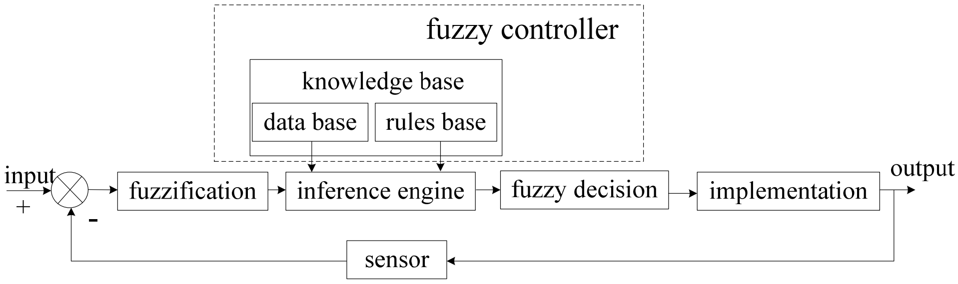

Figure 1. The schematic diagram of Fuzzy control principle

Fuzzy-PID control is the controller combined fuzzy control with traditional PID control, it is short for FPID. As the Figure 2 shows, the proportional gain, integral gain and differential gain of PID controller are the output of Fuzzy controller. The system error and error rate are the input of the fuzzy controller. In the process of PID control, K_P, K_I and K_D parameters are adjusted online by using fuzzy rules in order to meet the different requirements of deviation memory and deviation rate for PID parameters at different time. Combining Fuzzy control with PID control, and then we would get a system with dynamic rapid response, small overshoot [9] and strong anti-jamming ability. The structure of fuzzy adaptive PID Control system is as shown in Figure 2.

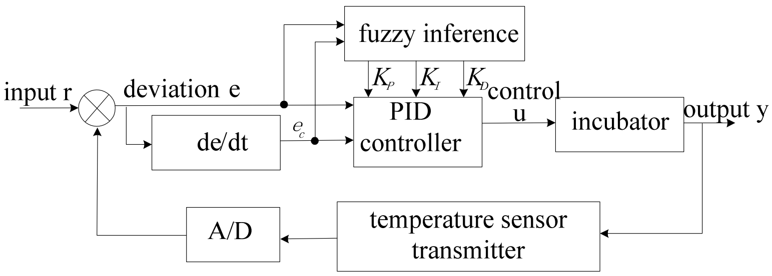

Figure 2. The structure of Fuzzy adaptive PID Control system

As a linear controller, the conventional PID controller's discrete control law is Formula (1).

$$u(k) = K_P e(k) + K_I \sum_{i=0}^{k} e(i) + K_D[e(k) - e(k-1)] + u(0) \tag{1}$$

In the controlled process of the system with different e and e_c, the setting principles of PID parameter [10] are as follows:

(1) When deviation $|e|$ is large, in order to increase the system response speed and has fast tracking performance, the system should be taken larger K_P and smaller K_D. At the same time, in order to prevent integral saturation and the too large overshoot, the system should be limited the size of K_I or made it to zero.

(2) When the deviation $|e|$ and $|e_c|$ are medium, in order to make the system has small overshoot, we should take small K_P, proper K_I and K_D. The value of K_D can affect the system reaction times greatly (Generally, its value is small.).

(3) When the deviation $|e|$ and deviation rate $|e_c|$ are small, in order to make the system has a good steady-state behavior, we could take larger K_P and K_I. Also in order to avoid oscillations near the equilibrium point of the system, we should take K_D properly. If e_c is large, take small K_D. If e_c is small, take large K_D.

Considering the above principles, in this design, fuzzy controller uses the structure of two inputs and three outputs. Deviation e and deviation rate are the inputs of the system. After they are quantified and fuzzy processed, querying the table of fuzzy control rules, then get fuzzy output K_P, K_I, K_D. After the defuzzication and quantification, we can get some accurate values. And the outputs together with the traditional PID will get the controlled quantity of the system. Considering the level of coverage and sensitivity of universe of discourse, and principles of robustness and stability, each fuzzy set membership function applies triangle membership function.

The fuzzy rules adopt that "if e is A and e_c is B then K_P is C and K_I is D and K_D is E". The fuzzy inference process of the controller parameters uses Mamdani [11] direct inference method. Defuzzication adopts weighted average method. Weighted average method gets the representative point, which is the center of the area made by fuzzy membership function curve and the abscissa. Theoretically, it should calculate the center of gravity of a series of points within the output scope. The formula is as Formula (2).

$$u = \frac{\int_x x\mu_N(x)\,dx}{\int_x \mu_N(x)\,dx} \tag{2}$$

But actually it calculates the center of gravity of several sampling points. The calculation formula is as Formula (3).

$$\overline{U} = \frac{\sum_{i=1}^{n} u_i \mu_u(u_i)}{\sum_{i=1}^{n} \mu_u(u_i)} \tag{3}$$

With deviation e and deviation rate e_c, it is possible to programmatically find the K_P, K_I, and K_D fuzzy matrix, which are the inputs of PID controller.

3. The Hardware Circuit Design of Incubator Temperature Control System

3.1. The Advantages of FPGA

Temperature control often uses microcontroller or MCU as the core control system. Compared to the hardware system, the system that applies the software control and operation has lower speed, poorer real-time performance and lower reliability.

FPGA is a new type of digital logic device with high integration, repeatable programmed, good performance of logic implementation, flexible design and other features. Using the internal logic module units to realized the functions that system required. Each module is parallel operated, which makes the system has great speed, strong real-time performance. The internal structure of FPGA can realize parallel computing.

3.2. Hardware Circuit Design of the System

The design uses Altera's Cyclone series FPGA devices EP1C12 as the core controller to measure and control the temperature of the incubator. Through the keyboard input set temperature to the FPGA. The field temperature parameters are sent through the process that thermocouple sensors are converted into EMF signal that filtered by the A/D converter, the real-time digital measurement value is sent to FPGA. FPGA can compare the set value with the measured value of temperature. After processed by fuzzy adaptive PID control algorithm, it outputs the corresponding control signal to ensure the temperature of incubator always remains within the set range. LCD used for real-time display of the control system temperature, the curve of temperature change, parameter configuration, and other information. The keyboard is used to set initial value of the control system and the information of initial parameters. Flash, SDRAM and I^2C are used for storage space extension. Figure 3 is the system hardware structure diagram.

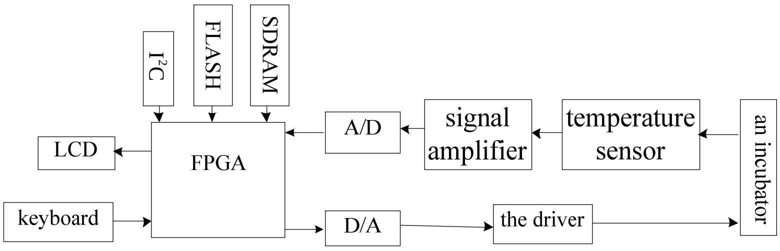

Figure 3. The system hardware structure diagram

3.3. The Internal Logic of FPGA

FPGA also includes the NIOS II software processor that provided by Altera Company. FPGA can communicate through internal dual-port RAM to its internal hardware module, and access control module status information and configure its parameters. On the other hand, it can monitor display module and keyboard module. The internal logical diagram of FPGA is shown in Figure 4.

Fuzzy adaptive PID control module is the core of the entire control system. It can achieve fuzzy parameter self-adjusting PID control algorithm. In order to achieve real-time control of the computer, the method we used is offline calculation and online look-up table. If necessary, only need to modify the control algorithm module and reconfigure the FPGA parameters, and then control algorithm upgrade can be achieved.

The internal hardware logic control modules of FPGA are programmed by VHDL hardware description language. VHDL is a top-down design approach with excellent portability. EDA platform has many characteristics like the versatility and independence of specific hardware structure. Unlike a computer program executed by the conventional sequence, VHDL executed concurrently, which can largely improve the processing speed of the adaptive PID temperature control, the design efficiency and temperature control effect.

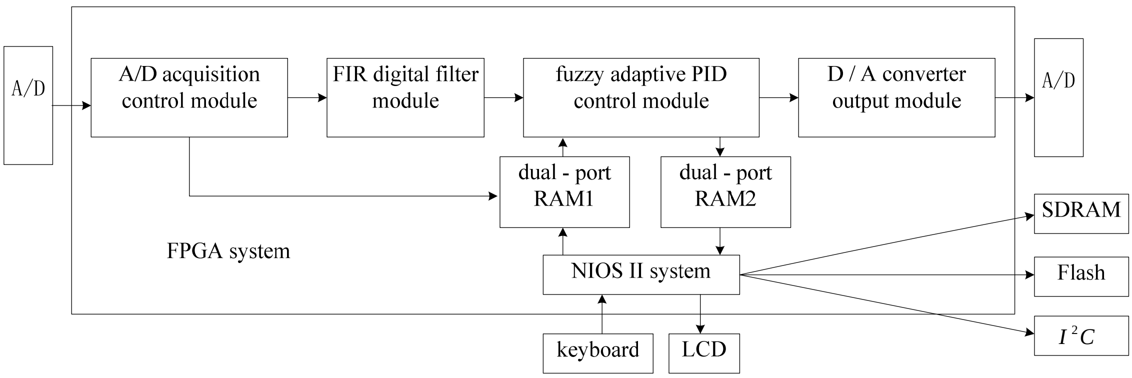

Figure 4. The internal logical diagram of FPGA

4. Software Design

4.1. The Overall Structure of System Software

The embedded software based on NIOS soft core CPU written program uses the C language. The Program design of the entire system, including: 1, the main program design of the controller, which is mainly declaring and initializing the display and the design of fuzzy PID program; 2, man-machine interface programming, which mainly includes the program design of the LCD and the keyboard; 3, temperature detection module includes the AD conversion program. The overall process is shown in Figure 5.

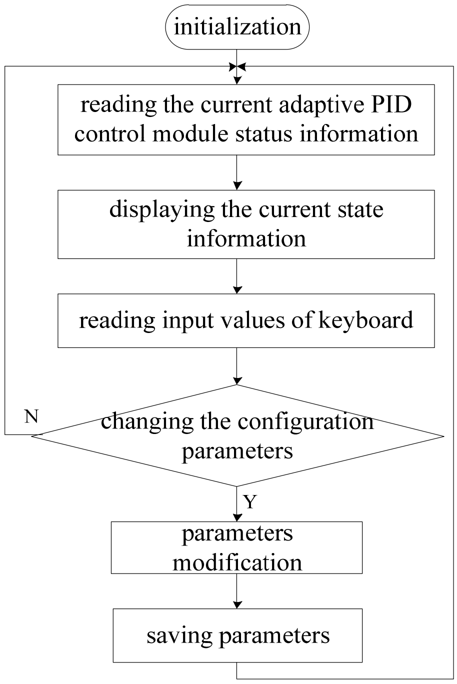

Figure 5. The overall flowchart of the software

After the power on run of the temperature control system, the first is to initialize system, and then the fuzzy adaptive PID control module reads duplex RAM1to gain the initial parameters information of controller and controls operation.

According to the operation results, the LCD screen will display the current temperature control system parameter and the change of temperature curve and current status information. At the same time, the real time control parameters and status information will be written into the duplex RAM2 and saved. After that, NIOS soft-core processor will read data from the RAM2, and get the current state information of fuzzy adaptive PID control module. If the keyboard input setting temperature value again and when the system read the value, it will automatically inquire the fuzzy control rules table and modify the parameters value of duplex RAM1, recalculating with the fuzzy adaptive PID control module, and input the new parameters and real time status information of system to duplex RAM2 and feedback to NIOS soft core. If no keyboard input, the system state remains the same.

4.2. The Implement of Fuzzy PID Control Algorithm

According to the fuzzy PID rules, after the fuzzification of the traditional PID control parameters would get fuzzy PID. Because of the complexity of fuzzy control, this design uses the look-up table method. That is to say, the fuzzy control algorithm is used to calculate the output in the offline state according to different values. And then make it into a table stored in the control chip. Assuming the target setting temperature of the incubator is Ta, and the temperature that the temperature sensor detects is T, so that error e (e=T-Td) can be obtained. The deviation allows a maximum of 0.5 °C. And by using the fuzzy rules make the deviation fuzzed. The fuzzy table of values of the temperature deviation e is Table 1.

Assumes that the two measured system deviations are e1, e2, and the deviation rate is e_c = (e1-e2) / T. T is the sample-period, the allowed deviation is 0.2 °C. The temperature deviation rate fuzzy numerical are shown in Table 2.

Defining the fuzzy subset with the membership function [12], this design uses a high sensitivity of the trigonometric function as membership function that is shown in Figure 6.

Table 1. The fuzzy table of values of the temperature deviation e

variation range（℃）	Linguistic Terms	universe of discourse
2.5~5.0	PB	+6
1.0~2.5	PM	+4
0.5~1.0	PS	+2
-0.5~0.5	ZO	0
-1.0~-0.5	NS	-2
-2.5~-1.0	NM	-4
-5.0~-2.5	NB	-6

Table 2. Temperature deviation rate fuzzy numerical tables

variation range（℃）	Linguistic Terms	universe of discourse
1.2~2.4	PB	+6
0.4~1.2	PM	+4
0.2~0.4	PS	+2
-0.2~0.2	ZO	0
-0.4~-0.2	NS	-2
-1.2~-0.4	NM	-4
-2.4~-1.2	NB	-6

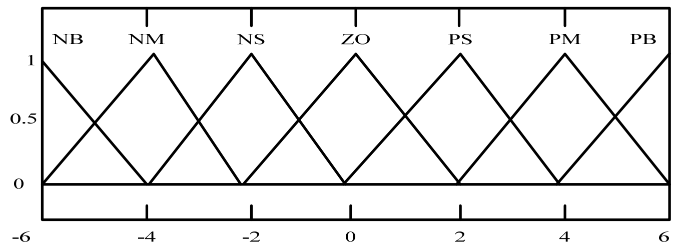

Figure 6. Membership function

All control commands of fuzzy PID control are implemented with fuzzy calculation of the table, so the fuzzy table calculation data related to the output of the controller. The design of fuzzy table mainly includes the following aspects:

1. Make sure the amount of input and output of the controller clearly.
2. Make sure the output and input of quantitative level, quantitative factors and the universe of discourse clearly.
3. In the domain of quantification of input and output variables define the fuzzy subsets.
4. Determine the fuzzy control rules and the establishment of the fuzzy control rule table.
5. Obtained fuzzy control table.

In this design, fuzzy PID controller changes various parameters by calculating the deviation and deviation rate. There are three fuzzy control tables, that is, ΔK_P、 ΔK_I and ΔK_D. They are obtained by calculating the deviation and the deviation change rate. Eventually we can obtain the fuzzy control tables of ΔK_P, ΔK_I and ΔK_D that as shown in Table 3, 4, 5.

4.3. The Design of Fuzzy Adaptive PID Software

The main input signal of Fuzzy control algorithm submodule generates from the deviation and deviation rate of the sub-module. The outputs of the latter, which are deviation e and deviation rate, are the input of the former. After fuzzy quantization, we can get fuzzy query address, fuzzy inference. After the defuzzification, we can get three parameters incremental value of the incremental PID operation. Then the parameters process that sum of the initial tuning parameters leads to the three incremental PID parameters. The control algorithm process is shown in Figure 7.

Table 3. Table of ΔK_P fuzzy control rule

e	ec						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PB	PM	PM	ZO	ZO
NM	PB	PM	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NM
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	ZO	ZO	NS	NS	NS	NB	NM
PB	ZO	ZO	NM	NM	NM	NB	NB

Table 4. Table of ΔK_I fuzzy control rule

e	ec						
	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NM	NM	NS	ZO	ZO	ZO
NM	NB	NB	NS	NS	NS	ZO	NS
NS	NM	NS	NS	NS	ZO	NS	NS
ZO	NM	NM	NS	ZO	PS	NS	NS
PS	NS	NS	ZO	PS	PM	NM	NM
PM	ZO	NS	PS	PS	PM	NB	NB
PB	ZO	ZO	PM	PM	PM	NB	NB

Table 5. Table of ΔK_D fuzzy control rule

e	ec						
	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NS	NB	NM	ZO	ZO	ZO
NM	NM	NS	NB	NM	NS	ZO	NS
NS	NS	NS	NM	NS	ZO	NS	NS
ZO	ZO	NS	NS	ZO	PS	NM	NM
PS	PS	ZO	ZO	PS	PS	NM	NM
PM	PM	PB	NS	PS	PM	NM	NB
PB	PB	PB	PM	PM	PM	NB	NB

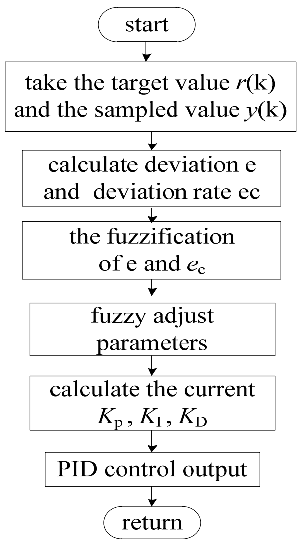

Figure 7. The flowchart of fuzzy adaptive PID control algorithm

5. Simulation of Fuzzy Adaptive PID Temperature Control System

With using the MATLAB fuzzy logic toolbox and Simulink to simulate the fuzzy adaptive PID temperature control system. Figure 8 is the comparison of fuzzy adaptive PID and traditional PID. And transfer function of the simulation model is $[1/(s^3+7s^2+15s+9)]exp(-1)$. Compare the simulation result of the fuzzy adaptive PID and traditional PID. The result is shown in Figure 9. Fuzzy adaptive PID control has shorter adjustment time, faster response, smaller overshoot and better static and dynamic performance than traditional PID control.

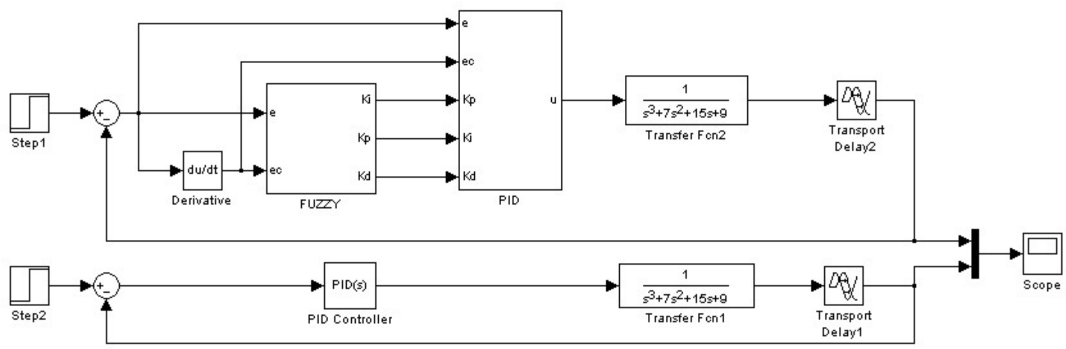

Figure 8. Simulation model of fuzzy adaptive PID temperature control system

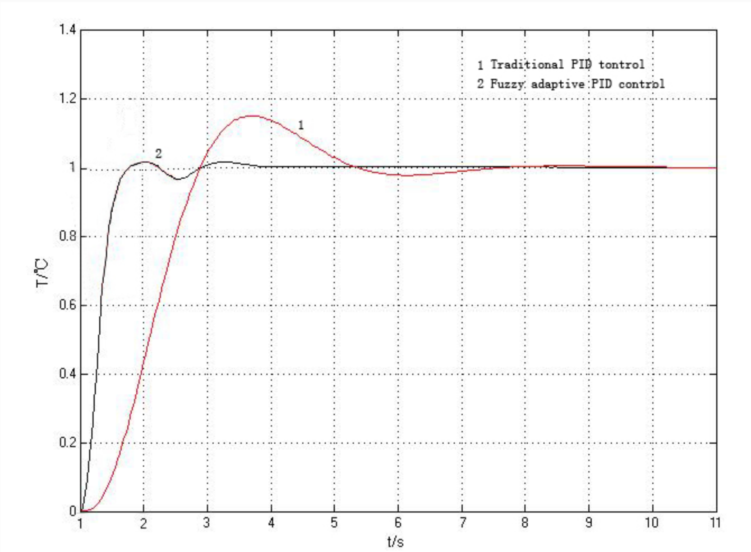

Figure 9. The comparison of Fuzzy adaptive PID and traditional System simulation

6. Actual Operating Results and Problems

Set a target temperature of the incubator which is 80 ° C. The regulation time in the running system is 400s. The overshoot is 5%. Add a step interference signal to the system when it is stable. The system is re–stabilized after nearly 300s. And there is less volatile produced in this process. Therefore, for the big inertia and big lag temperature control system, the temperature fuzzy adaptive PID controller that based on FPGA can achieve good control effect and adaptive ability. However, in the controller application process, there are still some problems, such as the optimization of the fuzzy rules and membership functions, and the enhancement of the system anti-interference performance. Therefore, this control system still needs to be perfected and further modified.

7. Conclusion

This design uses the high density of programmable logic devices. Based on the traditional PID controller, it takes the advantages of fuzzy control in order to control the temperature of the incubator. The result shows that the control system has a good static and dynamic performance and robustness. It has a very good adaptability for time-varying parameters. The amount of real-time computation is small and adjustment is convenient. It has a good upgrade performance, flexibility and good application prospect in the market as well.

References

[1] Li Yuhai, Du Hui, Huang Jing. The Design and Information of Realtime Information Distribution System Based on Web. *Science & Technology Progress and Policy*. 2005; 22(6): 153-155.
[2] Fang Zongshun, Hu Qiang, Zhao Yingkai. Real Time Information System based on the Web for the Yang ZI Company. *Industrial Control Computer*. 2003; 16(2): 12-14.
[3] Zhang Weicun, Chen Shuxin, Huang Chongguo. *Virtual Equivalent System For Self-Tuning Control*. Proceedings of the 24th Chinese control Conference, South China University of Technology. 2005.
[4] Zhu Jing. *Fuzzy Control Principles and Applications*. China Machine Press. 1995.
[5] Xu Xiangyuan. *Adaptive Control Theory and Applications*. Electronic Industry Press. Beijing, 2007.
[6] Tao Yonghua, Yin Yixin, Ge Lusheng. *A new PID control and its application.* Industrial Instrumentation & Automation. Beijing, 1998.
[7] Chuanhui Zhang, Xiaodong Song. The Self-Adaptive Fuzzy PID Controller in Actuator Simulated Loading System. *TELKOMNIKA Indonesian Journal of Electrical Engineering.* 2013; 11(5): 2619-2625.
[8] DW Clarke, PJ Gawthrop. Self-turning controller proceedings. *IEEE*. 1975; 12(9): 929-934.
[9] Dai Wenzhan, WU Xialai. An improved generalized predictive control algorithm for last restraining overshoot. *CIESC Journal*. 2010; 61(8).
[10] Fuzhen XIE, Jufang HU, Ping CHEN. Research on the Parameter Optimization of PID Controller. *AISS*. 2012; 4(2): 267 - 274.
[11] Zaid Amin Abduljabar. Simulation and Design of Fuzzy Temperature Control for Heating and Cooling Water System. *JACT*. 2011; 3(4): 41-48.
[12] Yueshan Wang, Liwan Chen, Zenghan Chen. A Fuzzy Self-tuning Controlled Feeding Servo System of Machine Tool. *TELKOMNIKA Indonesian Journal of Electrical Engineering.* 2013; 11(5): 2351-2358.