Network Controller Design and Analysis Based on Fuzzy Control Theory

Liping Lu

***Abstract*—**In order to improve the stability and control performance of network control system, this paper establishes the model of network control system by using Simulink module and TrueTime toolbox, designs network control system with time delay, analyzes different control algorithms of controller, obtains the output signal of network control system by using PID control algorithm, acquires the output signal of network control system by using fuzzy PID control algorithm, gets the output signal of network control system by using fuzzy T-S PID control algorithm; Through calculation and analysis, we find that when network control system has longer time delay, the fuzzy PID control algorithm and the fuzzy T-S PID control algorithm have better adaptability and control effect, the output signal of network control system by using fuzzy T-S PID control algorithm and fuzzy PID control algorithm have smaller overshoot and shorter adjustment time, and reaches quickly stability, but the output signal of network control system by using PID control algorithm has bigger overshoot and longer adjustment time or even instability, the experimental result shows that the fuzzy T-S PID control algorithm and the fuzzy PID control algorithm can compensate time delay and improve the stability of network control system.

***Keywords*—network control system, fuzzy controller, time delay, stability.**

I. INTRODUCTION

With the rapid development of electronic, communication and computer technology, the intelligent sensors, actuators and drive devices has laid the material foundation for network control system and control system has begun to gradually develop from closed centralized system to the open distributed system, takes shape network control system[1]. The system network installs sensors, controllers and actuators, which are devices with network interfaces, these devices are independent nodes in the network control system, each node transmits information through the network, reaches remotely control of controlled objects in different network links sensors, controllers and actuators distributing in different geographical locations, makes the control system develop from the closed system to fully distributed real-time feedback closed-loop control system, which is the network control system[2]. The advantage of network control system have resource sharing and remote distribution control, the system construction is modular, integrated, low cost, convenient for fault diagnosis and maintenance, easy to expand and flexible [3]. According to the existing simulation tools, TrueTime toolbox is an ideal network control system simulation toolbox, constructs the dynamic simulation of distributed real-time control system, control task execution and network interaction, analyze scheduling algorithms and control algorithms of network control system [4].

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II. DESIGN CONTROLLER

A. The Principle and Model of Fuzzy PID Controller

We design the fuzzy Proportional Integral Differential control algorithm in the network control system, which can reduce the time delay and the packet loss rate of network control system, Proportional Integral Differential control algorithm are called PID control algorithm, the principle structure of network control system based on fuzzy PID controller is shown in Figure 1.

In Figure 1, the difference of given input value and feedback value, which is called e, the rate of change for difference of given input value and feedback value is known as ec, $ec = de/dt$, e and ec are used the input of fuzzy PID controller, gets on obfuscation, the reasoning, the decision, and then outputs three control parameters of PID controller, there are the micro-variable value of Proportional, the micro-variable value of Integral, the micro-variable value of Differential, through the PID controller outputs control signal of network control system, the control signal transmitted to actuator through network, the actuator performs appropriate action to control controlled object. Among them, the micro-variable value of Proportional is described as ΔK_P, the micro-variable value of Integral is named as ΔK_I, the micro-variable value of Differential is defined as ΔK_D, the quantization factor of the fuzzy controller deviation is named as K_1, the quantization factor that the rate of change for difference of given input value and feedback value is called K_2, K_1 and K_2 are used to control input signal, the fuzzy controller actually adjusts these parameters, which are proportional parameter, integral parameter and differential parameter, K_P is proportional parameter, K_I is integral parameter, K_D is differential parameter. Fuzzy controller can use the experience to adjust proportional coefficient, integral coefficient and differential coefficient, make the entire control system based on PID controller to run better, steady [5].

The control law of PID controller is shown in formula (1).

$$u(t) = K_P[e(t) + \frac{1}{T_I}\int_0^t e(t)d_t + T_D\frac{d_{e(t)}}{d_t}] \quad (1)$$

In (1), K_P is the proportional time constant, T_I is the integral time constant, T_D is the differential time constant, the formula (1) turns to formula (2).

$$u(t) = K_P e(t) + K_I \int_0^t e(t)dt + K_D \frac{d_{e(t)}}{dt} \qquad (2)$$

We use fuzzy language expression the non-linear relationship between the difference of given input value and feedback value, the rate of change for difference of given input value and feedback value, and proportional time constant, integral time constant, differential time constant [6].

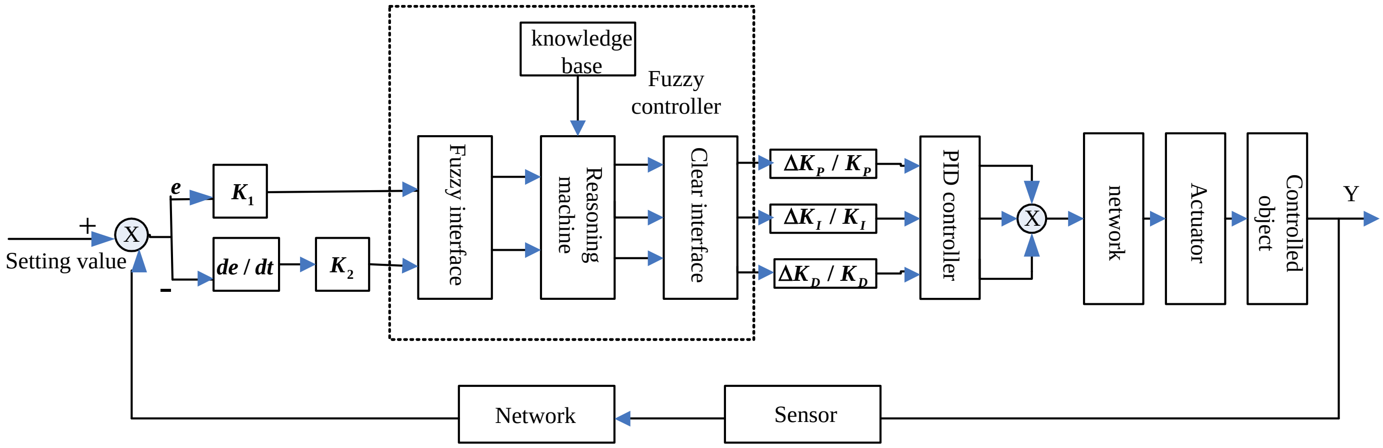

Figure 1. The principle structure of network control system based on fuzzy PID controller

The establishment of simulation model, which constantly adjusts the correlation coefficient of each module, we obtain the statement between the difference of given input value and feedback value, the rate of change for difference of given input value and feedback value, and proportional time constant, integral time constant, differential time constant of the PID controller[7].

When $|e(t)|$ is larger, in order to approach the given value as soon as possible, namely, we can increase appropriately the proportional time constant, reduce appropriately the difference time constant, the integral time constant, or make the difference time constant and the integral time constant to zero, ensure the network control system to quick response[8].

When $|e(t)|$ is the medium value, in order to control the higher precision of controller, we should increase properly the difference time constant to facilitate the better elimination of static error of network control system [9].

When $|e(t)|$ is smaller, in order to improve the stability of network control system, we can increase appropriately the proportional time constant and the integral time constant [10].

The fuzzy PID controller selects the difference of given input value and feedback value and the rate of change for difference given input value and feedback value, which are used input signal, the value of linguistic variable are defined as NB, NM, NS, Z0, PS, PM, PB, we select the three parameters of micro changes are applied as output signal, NB, NM, NS, Z0, PS, PM, PB take as seven fuzzy values. According to the running status of network control system, we determine control rules of fuzzy PID controller, which is shown in Table 1. Among, NB is the negative and big of difference of given input value and feedback value, and the rate of change for difference of given input value and feedback value, NM is the negative and medium of difference of given input value and feedback value, and the rate of change for difference of given input value and feedback value, NS is the negative and small of the difference of given input value and feedback value, and the rate of change for difference of given input value and feedback value, Z0 are the difference of given input value and feedback value and the rate of change for difference of given input value and feedback value, PS is the positive and small of difference of given input value and feedback value, and the rate of change for difference of given input value and feedback value, PM is the positive and medium of difference of given input value and feedback value, and the rate of change for difference of given input value and feedback value, PB is the negative and big of difference of given input value and feedback value, and the rate of change for difference of given input value and feedback value, ΔK_P is the micro changes of proportional time constant, ΔK_I is the micro changes of integral time constant, ΔK_D is the micro changes of differential time constant.

The Fuzzy controller model of network control system is realized through the TrueTime Kernel module, the Network module and Simulink module interconnection to achieve. The three modules are used to establish the fuzzy controller independent module first, and then the fuzzy controller is connected with PID controller, the three parameters of PID controller can be adjusted, finally, the control signal can be output of fuzzy PID controller. The complete fuzzy PID controller model is shown in Figure 2, and is embedded in network control system model, Table 1 shows the control rules of Fuzzy PID controller.

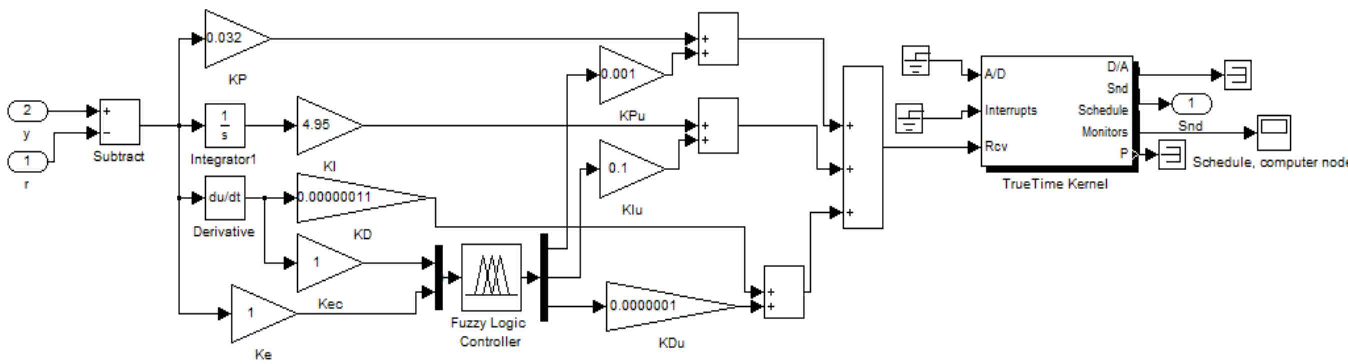

Figure 2. The model of fuzzy PID controller

Table 1. The control rules of Fuzzy PID controller

ec / ΔK_P ΔK_I ΔK_D / e	NB	NM	NS	ZO	PS	PM	PB
NB	PB PB	PB PB PB	PB PS PM	PM PS PM	PM PS PM	PM PS PM	PS PS PS
NM	PB PS PB	PB PS PS	PM PS PM	PM PS PM	PS PS PS	PS PS PS	ZO ZO ZO
NS	PM PB PS	PM PB PS	PM PM PS	PS PS PS	ZO NM ZO	ZO NM ZO	ZO NM ZO
ZO	PM PM ZO	PM PM ZO	PS PM ZO	ZO ZO ZO	NS NM ZO	NM NM ZO	NM NM ZO
PS	ZO PM ZO	ZO PM ZO	ZO PM ZO	NS NS NS	NM NM NS	NM NB NS	NM NB NS
PM	ZO ZO ZO	NS NS NS	NS NS NS	NM NS NM	NM NS NM	NB NS NB	NB NS NB
PB	NS NS NS	NM NS NM	NM NS NM	NM NS NM	NB NS NM	NB NB NB	NB NB NB

B. The Principle and Model of T-S Fuzzy Controller

The T-S fuzzy model, which propose by Takagi and Sugeno, is the inheritance and development of the Mamdani-type fuzzy mode. The connection between Sugeno-type fuzziness and Mamdani-type fuzziness that the fuzzy rules of antecedents are fuzzy set, the biggest difference between Sugeno-type fuzziness and Mamdani-type fuzziness is the difference of output conclusions. Mamdani-type fuzziness output is the fuzzy subset, while Sugeno-type fuzzification output is the exact linear function[11-12].

Supposing that the input variable of T-S fuzzy model is x, $x=[x_1,x_2,\ldots,x_n]^T$, the fuzzy set of each component x_j is expressed in formula (3).

$$T(x_i)=\left\{A_i^1,A_i^2,\ldots,A_i^n\right\} \tag{3}$$

In (3), A_i^j is a linguistic fuzzy set of x_i and its hose membership function is $\mu_{A_i^j}(\mathrm{x}_i)$.

The i fuzzy rule of T-S fuzzy model is as follows:

$$R^i:\text{if } x_1=A_1^i \text{ and } x_2=A_2^i \text{ and } \ldots\ldots x_n=A_n^i\text{,then}$$
$$y^i=b_0^i+b_1^i x_1+\cdots+b_n^i x_n \tag{4}$$

In (4), y^i represents the output of the i rule in the T-S fuzzy model.

The fitness of each rule is defined by (5).

$$\alpha_j=\mu_{A_1^j}(\mathrm{x}_1)\wedge\mu_{A_2^j}(\mathrm{x}_2)\ldots\wedge\mu_{A_n^j}(\mathrm{x}_n) \tag{5}$$

The final output of T-S fuzzy model is the weighted average of each fuzzy rule, it is shown in (6).

$$y=\frac{\sum_{j=1}^{m}a_j y_j}{\sum_{j=1}^{m}\alpha_j} \tag{6}$$

After the piece of T-S fuzzy model is a linear function, the classic PID transfer function is linear. Therefore, the PID controller based on T-S fuzzy model is feasible. From the control theory, the pre-variables of TS-PID model can choose the deviation, the rate of deviation's change and the deviation integral, which are defined as input variables, the rules is shown in formula (7).

$$R^i:\text{if } e=A_1^i \text{ and } \Delta e=A_2^i \text{ and } \int edt=A_3^i,\quad\text{then}$$
$$y^i=K_P^i e+K_D^i\Delta e+K_I^i\int edt \tag{7}$$

In (7), K_P^i, K_D^i and K_I^i respectively represents the proportional coefficient, differential coefficient, integral coefficient for the i rule[13-15].

We design the fuzzy controller, determine the input signal and output signal of fuzzy controller. The deviation e and the variation rate ec in the network control system is defined as the input variables, the output signal of controlled object is described as the output variable, we can get the two-dimensional fuzzy controller, and determine the experience value of each input variable[16].

In the networked control system, the domain of deviation e is defined as [-2,2] by observing PID control, and the quantization level is five levels ,which is NB, NS, Z0, PS and PB. The deviation of rate of change ec, which is [-3,3], the quantization level of three are N, Z0, P. The selection of membership function commonly uses triangular membership function.

The establishment of fuzzy control rules is realized through human experience. This paper establishes the relationship between the three parameters of practical control and PID control, and the relationship between system deviation e and deviation rate ec. Because this article uses T-S fuzzy control, that Sugeno-type fuzzy, so the output of the post-accurate is linear function, is defined by $f(u)$ function. Figure 3 shows the step response curve of system.

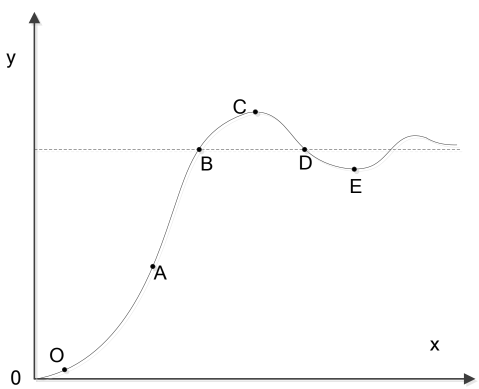

Figure 3. The step response curve of system

In Figure 3, the classical step response is divided into five different stages, and the three parameters of PID control and their relationship with the system deviation e and the deviation change rate ec also exhibit different characteristics in these five stages, therefore, the fuzzy rules of this article analyze the characteristics of the five stages, formulate the general direction of fuzzy rules based on the analysis.

The OA section is the first paragraph, because the system feedback detection value is less than the given value at this time, means the system deviation is greater than 0, the deviation rate of change is less than 0, so the proportion coefficient should be increased, the differential coefficient takes a negative value, in order to speed up the system's dynamic response.

The AB segment is the second paragraph, the system feedback detection value has been close to a given value at this moment, but the system deviation and deviation change rate is same with the first paragraph, should reduce proportional coefficient, correct positive and increase the differential coefficient to reduce the upcoming overshoot in this stage.

The BC section is the third paragraph, the system feedback detection value has exceeded a given value at this time, then the system deviation is negative but the deviation change rate is positive, so the system deviation is gradually larger, increase the proportion coefficient to suppress deviation, the differential coefficient is reduced in order to reduce overshoot.

The CD segment is the fourth paragraph, the system feedback test value is still above a given value at this moment, the system deviation is negative, the deviation change rate is negative, so the system deviation is gradually smaller, should be reduced proportion coefficient to prevent the callback occurs.

The DE segment and beyond is the fifth paragraph, the system has gradually stabilized at this time, should be reduced proportional coefficient and differential coefficient, the integral coefficient increases to eliminate the steady state error.

T-S fuzzy controller model shown in Figure 4, consists of two parts, the first part is the combination of T-S fuzzy controller and PID control parameter self-tuning fuzzy PID controller, its main role is to fuzzy control of the PID control P , I, D three parameters are processed and adjusted to meet the network control system different e and ec on the controller parameters of the different requirements, the second part of the network control system by the controller's real-time kernel module, its main role is received fuzzy PID controller-processed control signals in the Rcv port, and then send signals to the network control system network module via the Snd end.

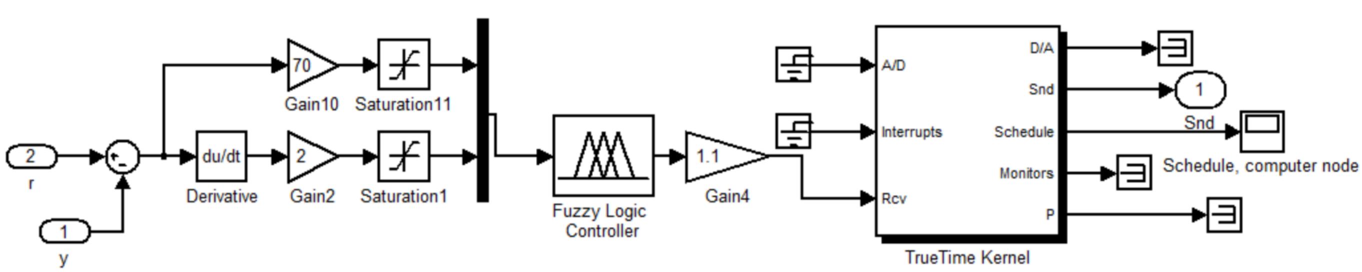

Figure 4. The model of T-S fuzzy controller

III. Computational Analysis

The model of network control system is established by using Simulink module library and the related module in Truetime toolbox. The sensor node periodically samples the output signal of the controlled object and sends the sampled data to the controller node through the network, the controller can make the corresponding action. The task of the controller node is to calculate the difference between the system setting value and the system output signal sent by the sensor and take the deviation as the controller input amount and output the control signal through the corresponding control algorithm, then send the control amount to the execution the node of the actuator, the actuator node perform corresponding actions on the controlled object according to different control signals.

Figure 5 shows that we build the network control system model based on PD controller, the system results of output curve is shown in Figure 8, and set up network control system model based on fuzzy PID controller is shown in Figure 6, using Fuzzy PID controller, the system results of output curve is shown in Figure 9, and build network control system model based on TS-fuzzy controller is shown in Figure 7, T-S fuzzy controller embedded the controller of Figure 6, the system results of output curve is shown in Figure 10.

Figures 5, 6 and 7 all have the same transfer functions for the controlled object in the network control system, the transfer functions is called $G(s)$.

$$G(s) = \frac{1000}{s*(s+1)} \tag{8}$$

In Figure 6, the fuzzy PID controller is embedded in the fuzzy controller, the specific fuzzy PID controller model structure is shown in Figure 3.

In Figure 7, T-S fuzzy controller is embedded in T-S fuzzy controller, the specific T-S fuzzy controller model structure is shown in Figure 4.

Supposing that the network interference is 0, the communication mode is set to Ethernet, the sampling period is 0.01s, the data transmission rate is 100kbit/s, the packet loss rate is 15% and the time delay is 0.12s. The results of the network control system is shown in Figure 8, the results of network control system is shown in Figure 8 based on the fuzzy PID controller.

From Figure 8 and Figure 9, we find that when the same packet loss rate and the same time delay exist in network control systems with different controller algorithms, the system output is distorted state using the general PID controller, namely, it can not guarantee the stable output of the system. The output of system with fuzzy PID controller has overshoot; it can eventually reach stable state. Therefore, compared with the general PID controller of network control system, the fuzzy PID controller of network control system has better performance adaptive ability.

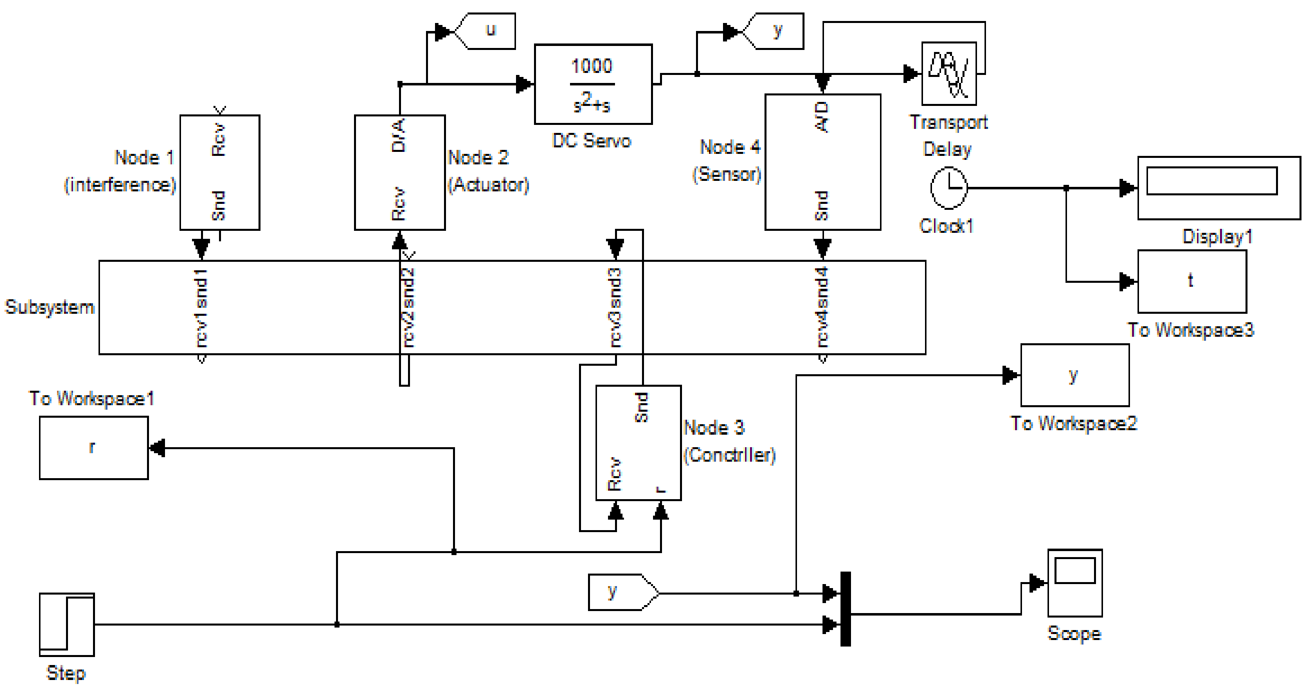

Figure 5. The model of network control system based on PD controller

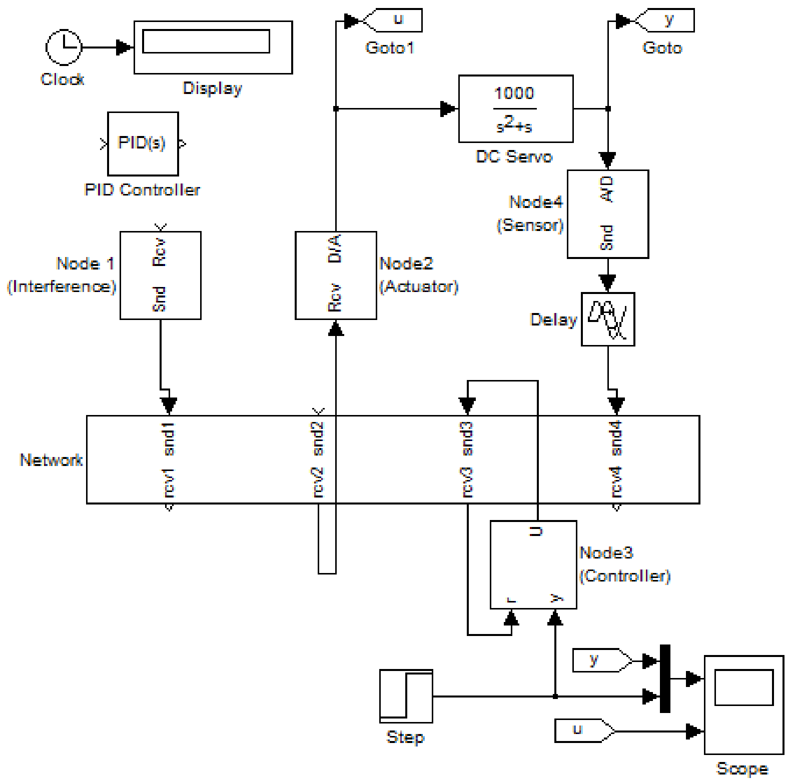

Figure 6. The model of network control system based on fuzzy PID controller

Assuming the network type is CAN bus, the data transmission rate is 800Kbits/s, the sampling period is 0.01s, the interference is 0.1 and the time delay is 0.001s. Figure 10 shows the results of the network control system based on PID controller, Figure 11 shows the results of the network control system based on T-S fuzzy controller.

We find from Figure 10 and Figure11, when the time delay is 0.001s, the system output curve is stable after 0.3s by using the general PID controller, while the system output shows the small overshoot, the adjustment time is only 0.2s, when we use the T-S fuzzy PID controller. It can be seen that the control algorithm by using T-S fuzzy model can effectively compensate the time delay and improve the control performance of network control system.

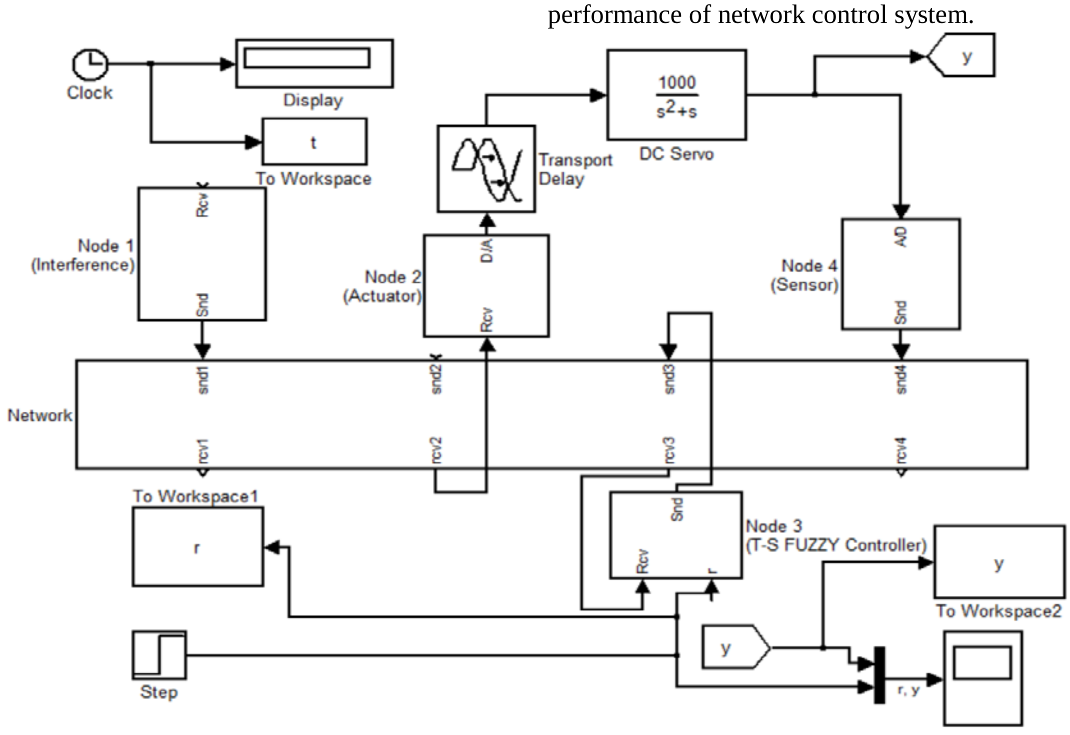

Figure 7. The model of network control system based on T-S fuzzy controller

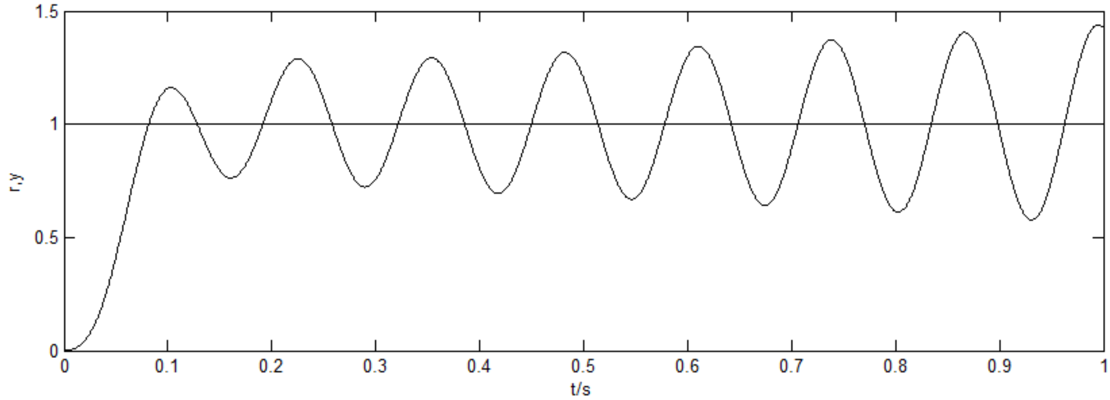

Figure 8. The output curve based on PID controller when time delay is 0.1s

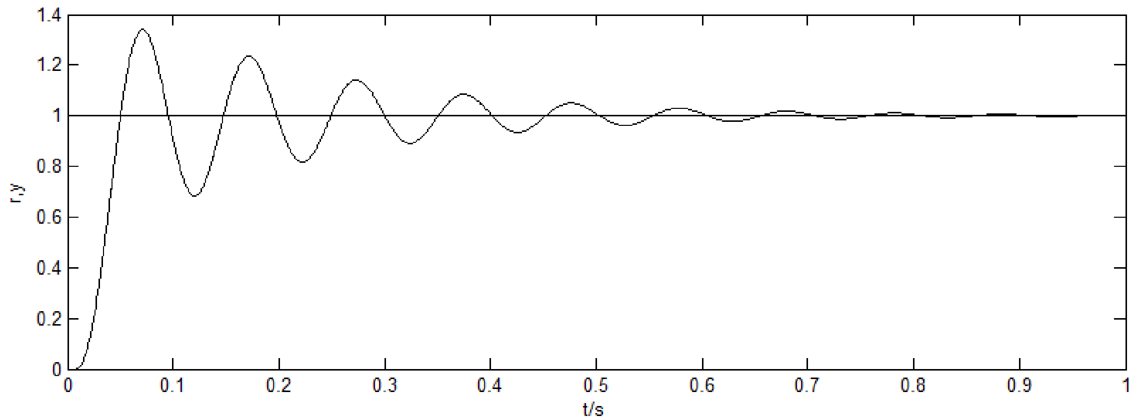

Figure 9. The output curve based on fuzzy PID controller when time delay is 0.1s

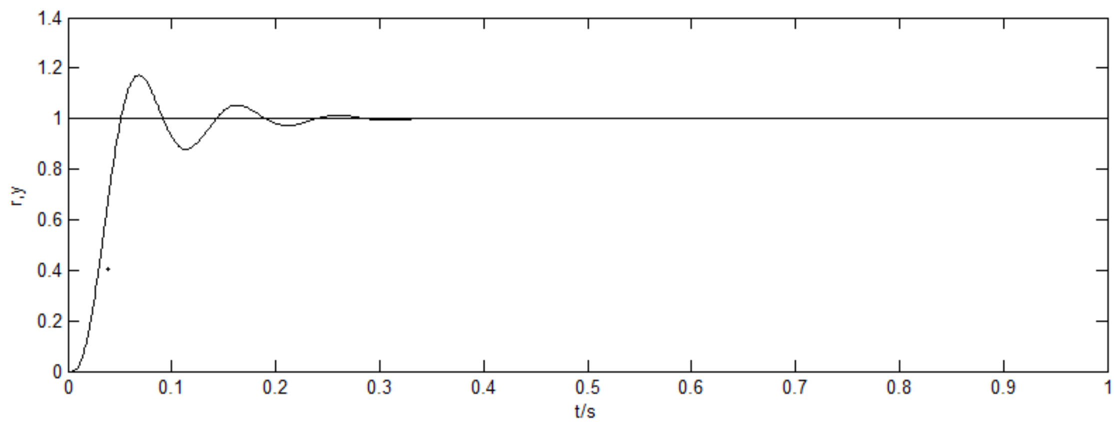

Figure 10. The system output curve using the PID controller

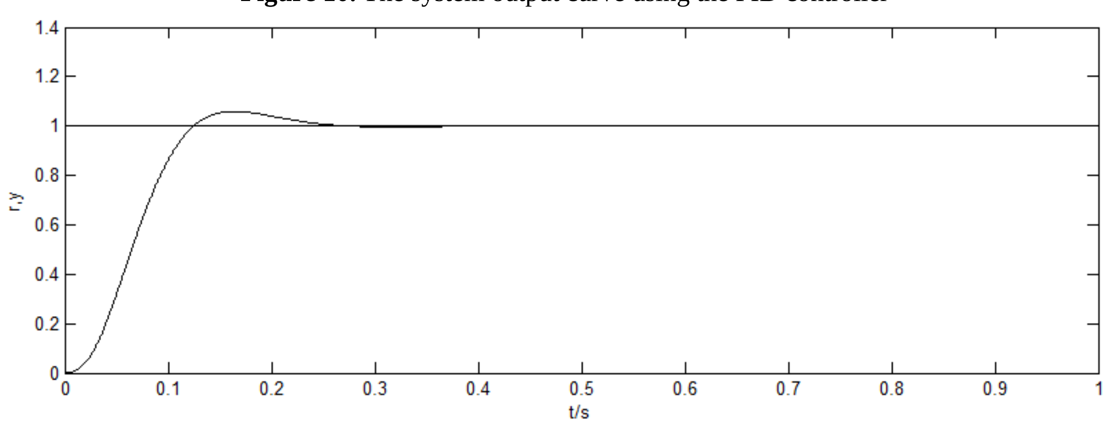

Figure 11. The output curve using T-S fuzzy controller

IV. Conclusion

The different control algorithm of controller has a great influence of control performance and stability in the network control system, in order to reduce overshoot and adjustment time, and improve control effect, this paper designs three control algorithms and applies to the network control system, establishes respectively the network control system model based on PID control algorithm of controller, fuzzy PID control algorithm of controller, and T-S fuzzy control algorithm of controller. Through simulation analysis, when the network control system has longer time delay, the output signal of network control system by using fuzzy PID control algorithm can reaches the stability, but the output signal of network control system by using PID control algorithm is instability. When the network control system has shorter time delay, the output signal of network control system by using fuzzy T-S PID control algorithm has smaller overshoot and shorter adjustment time, and becomes quickly stability, but the output signal of network control system by using PID control algorithm has bigger overshoot and longer adjustment time. Therefore, we find that the fuzzy PID control algorithm and fuzzy T-S PID control algorithm of network control system can effectively compensate for time delay, reduces the influence on the stability of network control system, makes the network control system has better self-adaptability and control quality.

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