Priority Scheduling of Networked Control System Based on Fuzzy Controller with Self-tuning Scale Factor

Zhongda Tian, Shujiang Li, Yanhong Wang, Bin Gu

Abstract—**A scheduling algorithm based on fuzzy controller with self-tuning scale factor for networked control system with resource constraints is proposed in this paper. The scheduling algorithm comprehensively considers output error and output error change rate of each control loop in the system. The fuzzy rules are memorized and realized by BP neural network. In order to improve the system ability of restraining the change of the external disturbance, this paper adopts the method of online self-tuning scale factor. The output scale factor is online tuned by the system running state. The priority of each control loop can be adjusted dynamically by the fuzzy controller with self-tuning scale factor. The priority of each control loop can meet the real-time requirement of the system. The simulation model is built based on True time toolbox. Compared with EDF and fuzzy feedback scheduling algorithm, the simulation results show that the proposed scheduling algorithm in this paper can improve the system output control performance, decrease the data transmission delay and integral absolute error value of the control loops, reduce the conflict of data transmission and network utilization. The overall control performance of the system is optimized. The priority scheduling algorithm in this paper is effective.**

Index Terms—**networked control system, priority, scheduling, fuzzy feedback, self-tuning scale factor**

I. Introduction

The networked control system is a real-time distributed closed-loop feedback control system include sensor nodes and the actuator nodes which are connected through a shared communication network [1]. Compared to the traditional point to point control system, networked control system is an opened and shared communication network, which each node can use this network communication to realize information exchange, resource sharing, and coordinated operation [2, 3]. The networked control system has the advantages of less connecting line, convenient installation and operation maintenance, remote operation and control, and high system reliability [4]. When using wireless network, networked control system can even realize some control functions with special purposes. Because of its remarkable characteristics, networked control system has become more and more popular with experts and scholars, and has achieved a lot of research results. Networked control system is now widely used in telemedicine, intelligent delivery, aerospace, manufacturing process, national defense and other fields.

However, the network is not a very reliable communication medium. Due to the limitation of network bandwidth and service capacity, the data in the network transmission inevitably have time delay, packet loss, data disordering and other problems. These problems are important reasons for the deterioration of system performance and the instability of networked control system. Therefore, the traditional control theory is too difficult to be directly applied to the analysis and design of networked control system [5, 6]. In recent years, many scholars focus on the research of networked control system with limited bandwidth. The bandwidth limitation is a very significant factor that affects the performance of the networked control system [7]. How to allocate the limited network source or design reasonable scheduler and achieve good control performance has become one of the popular research fields. At the same time, in one networked control system, the performance of each control loop not only depends on the design of the control algorithm, but also is affected by the scheduling algorithm of network resources [8]. Therefore, the scheduling algorithm plays an important role in the closed loop networked control system.

In these research results, how to design and determine the priority of control loop is an important issue. The excellent priority scheduling algorithm can reduce the possibility of message transmission conflict and improve the performance of system. The classical network priority scheduling algorithm usually determines the priority by the characteristic parameter of the task. They include try-once-discard (TOD) algorithm [9] and maximum error first (MET) algorithm [10]. These two algorithms make the nodes with the biggest transmission error preferred to transmit the data, and the other nodes discard the non transmission data. Yepez et al., proposes a large error first (LEF) dynamic scheduling algorithm. In EDF algorithm, the priority of the control loop will be determined by the difference between the actual response of the controlled object and the expectation value

Manuscript received November 19, 2016; revised June 08, 2017. This work was supported in part by the Science Research Project of Liaoning Education Department under Grant LGD2016009, Natural Science Foundation of Liaoning Province of China under Grant 20170540686 and National Key R&D Program of China under Grant 2016YFD0700104-02.

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[11]. Considering the messages deadline and importance, the Literature [12] determines the priority of the message. Under normal circumstances, the algorithm shows its optimality, but in the case of overload, the system will be a sharp decline in performance. In the [13], the author presents priority-based scheduling algorithm can accommodate more systems resources to transmission slots, which can decrease computational load and energy consumption. In case of resource scarcity, the scheduler probabilistically allocates the channel to those that exceed the local thresholds according to an error-dependent priority measure [14]. Numerical results indicate its effectiveness. In order to improve the quality of service (QOS) in networked control system, the author proposes a hybrid priority scheme for the message scheduling [15]. In order to improve the QoS and the QoC for CAN-based networked control system, Cac N T et al., propose a hybrid priority scheme for the message scheduling [16]. In the Literature [15] and [16], other performance indexes are not considered, so the study has a few limitations. The scheduling strategy is designed to change the task priority according to the transmission error over deadline task when applying dynamic EDF scheduling strategy [17]. The effectiveness of improved scheduling algorithm is verified by the simulations.

As an important branch of intelligent control [18], fuzzy control theory is introduced into the research of networked control system, and some achievements have been made in the study of fuzzy control theory. Fuzzy scheduling algorithm combines both static and dynamic characteristics, and it has stronger applicability. Based on the competition of network resources, Literature [19] and [20] adjust the priority of control loop through fuzzy feedback scheduling method. In order to bind time delays, the author presents a hierarchical scheduling priority exchange algorithm based on co-design strategy following mutual correlation algorithms [21]. The simulation is carried out through a magnetic levitation system. The author calculates the message priority of communicating message by a modified fuzzy maximum priority scheduling strategy based on feedback [22]. This fuzzy priority scheduling strategy takes loop control error, error change rate and network latency as the input of fuzzy control algorithm, and dynamically updates the priority of each loop in the networked control system.

One of the problems of these fuzzy feedback priority scheduling algorithms is that the output scale factor of the fuzzy controller is fixed in the running process of the algorithm. This will lead to severe change of the priority of the control loop. The priority switching is too frequent; the probability of the occurrence of the message conflict in the network will increase. Too frequent priority switch will be beneficial to the performance of some control loops, but it is harmful to the performance of the whole control systems. Based on the above discussion, this paper introduces the fuzzy control theory into the priority scheduling strategy, and proposes a dynamic fuzzy priority feedback scheduling with self-tuning scale factor based on the limited bandwidth allocation. The algorithm comprehensively considers the control error and error change rate of each control loop in the system. The priority of each control loop can be adjusted dynamically by self-tuning scale factor, which can meet the real-time requirement of the system. The simulation results show that the proposed scheduling method can improve the system performance, reduce the data transmission delay, integral absolute error of the control loop and network utilization of the system.

The main contents of this paper are as follows. Section 2 introduces the system structure of this paper. Section 3 designs the fuzzy feedback priority scheduler with self-tuning scale factor. The simulation results are provided in Section 4. The summary and prospects of the paper are summarized in Section 5.

II. SYSTEM STRUCTURE

The networked control system in this paper has multi loops, as showed in Fig. 1. In this system, a master node is used as the scheduler, which sends scheduling information to each sensor in real time. The sensor sends the new sampling information to the controller through the network [23]. At the same time, the sensor also sends these data to the scheduler. Considering the limited resources of the network, the information of the low priority control loop may not be updated for a long time, which leads to the deterioration of the control performance of the loop. This paper uses the error and error change rate of control loop, and determines the priority of the control loop combined with self-tuning scale factor. The priority of each control loop is constantly changed rather than fixed. Therefore, each control loop has the opportunity to update its information.

The control system used in this paper is described as follows.

1. Sensors use time-driven mode. Controllers and actuators use event-driven mode.
2. The priority of the sensor is used as the initial priority of the control loop.
3. The buffer queue in the sensors only holds the latest sample value.
4. The priority allocation strategy based on fuzzy control should be implemented on the network based on priority. In this paper, CAN bus is chosen as the simulation network.

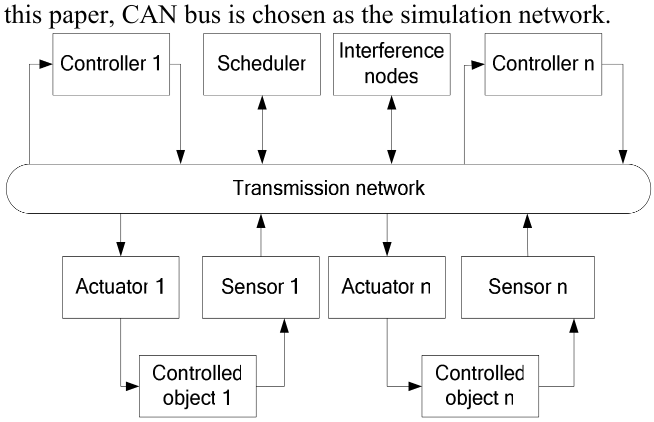

Fig. 1. The structure of fuzzy feedback scheduling system

III. FUZZY FEEDBACK PRIORITY SCHEDULER WITH SELF-TUNING SCALE FACTOR

Fig. 2 is the system structure of the fuzzy feedback scheduler with self-tuning scale factor proposed in this paper. r_i is system input, y_i is output feedback signal of each control loop, $prio_i$ is the priority of each control loop determined by the scheduler. Interference node will occupy a certain network bandwidth, which is used to realize the condition of limited resources.

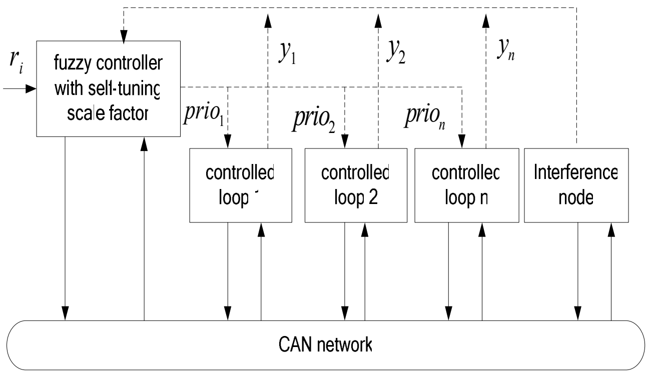

Fig. 2. The structure of fuzzy feedback priority scheduler with self-tuning scale factor

A. Input and output of fuzzy reasoning

A two-dimensional fuzzy controller with two inputs and one output is as shown in Fig. 3. The input variable is error of control loop, $e_i(k) = r_i(k) - y_i(k)$. The error change rate is $ec_i = e_i(k) - e_i(k-1)$. The output is priority of each control loop $prio_i$. $r_i(k)$ is reference input of *ith* control loop at time k, $y_i(k)$ is output of *ith* control loop at time k.

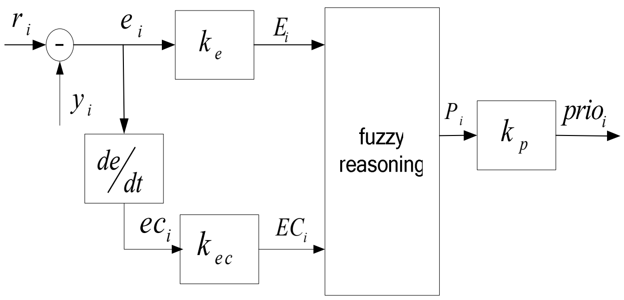

Fig. 3. The structure of fuzzy feedback priority scheduler with self-tuning scale factor

E_i is chosen as fuzzy set of input variable e_i, EC_i is chosen as fuzzy set of input variable ec_i, P_i is fuzzy set of output priority variable p_i. Actual variation range of e_i is [–1, 1], actual range of variation of ec_i is [–1, 1] and actual range of variation of p_i is [1, 5]. The quantization level of input E_i and EC_i is {–4, –3, –2, –1, 0, 1, 2, 3, 4}, the quantization level of output p_i is {1, 2, 3, 4, 5}. The scale factor k_e is 4, k_{ec} is 4 and k_p is 1.

B. Membership function of variables

The fuzzy subset number of e_i and ec_i is 5, that is {NB, NS, ZO, PS, PB}. The fuzzy subset number of P_i is 5, that is {PS, S, M, B, PB}. Where, NB means negative big, NS means negative small, ZO means zero, PS means positive small, PB means positive big, S means small, M means middle and B means big. Fig. 4 is the membership function curve of input variables E_i and EC_i. In this paper, the triangle membership function is used. Fig. 5 is membership function curve of output variable P_i. The Gauss membership function is utilized.

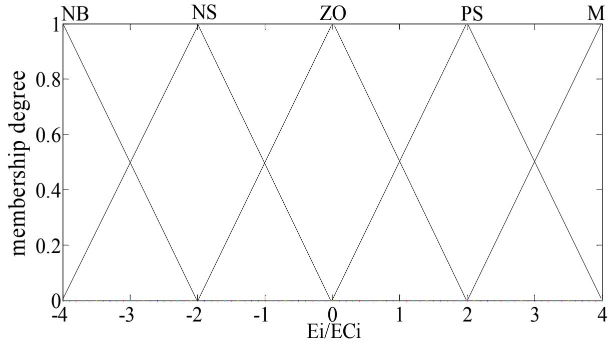

Fig. 4. Membership function curve of E_i and EC_i

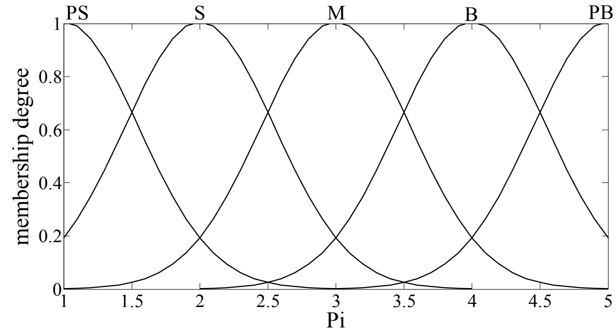

Fig. 5. Membership function curve of P_i

Table I is membership degree table of E_i and EC_i determined by their membership functions. Table II is membership degree table of P_i.

TABLE I

MEMBERSHIP DEGREE TABLE OF E_i AND EC_i

E_i / EC_i	-4	-3	-2	-1	0	1	2	3	4
NB	1	0.5	0	0	0	0	0	0	0
NS	0	0.5	1	0.5	0	0	0	0	0
ZO	0	0	0	0.5	1	0.5	0	0	0
PS	0	0	0	0	0	0.5	1	0.5	0
PB	0	0	0	0	0	0	0	0.5	1

TABLE II

MEMBERSHIP DEGREE TABLE OF P_i

P_i	1	2	3	4	5
PS	1	0.2	0	0	0
S	0.2	1	0.2	0	0
M	0	0.2	1	0.2	0
B	0	0	0.2	1	0.2
PB	0	0	0	0.2	1

C. Fuzzy control rules

The fuzzy control rules are obtained according to the analysis of the control performance [24]. The greater the error and the error change rate of the control loop, the higher the priority of the loop. The greater the error e_i, the control loop requires more bandwidth resources to transmit data. In order to improve the control performance of the loop, a higher priority will be assigned. If the positive and negative of e_i

and ec_i are the same, indicating that the error has an increasing tendency, the control loop should be given a relatively higher priority. If the positive and negative of e_i and ec_i are not the same, indicating that the error has a decreasing tendency, the control loop should be given a relatively lower priority. According to this idea, the fuzzy control rules are obtained. Table III shows the fuzzy rules.

TABLE III
FUZZY RULES

P_i		E_i				
		NB	NS	ZO	PS	PB
EC_i	NB	PS	PS	S	PB	PS
	NS	PS	S	M	B	PS
	ZO	PS	M	PB	M	PS
	PS	PS	B	M	S	PS
	PB	PS	PB	S	PS	PS

The priority of the loop is calculated by using a neural network, which realizes those memory fuzzy rules. The neural network is a multilayer feed forward BP neural network with a hidden layer. The input of neural network is fuzzy subset of error E_i and error change rate EC_i. The output of neural network is quantization value of fuzzy subset of P_i. The structure of BP neural network is indicated in Fig. 6.

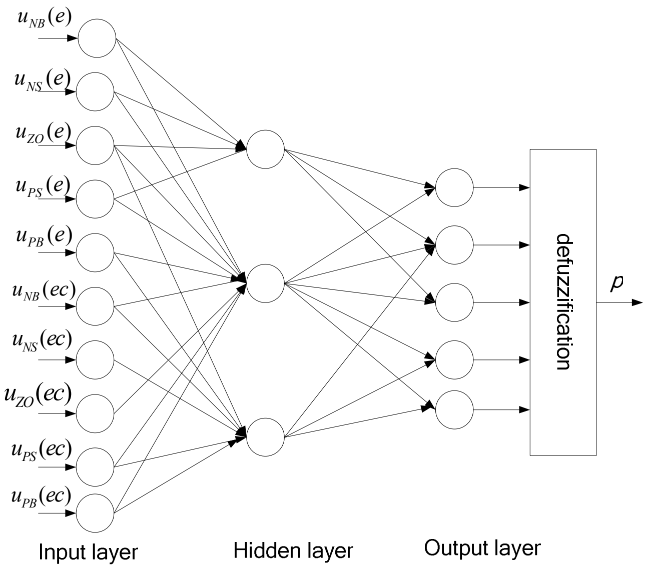

Fig. 6. The fuzzy rules implementation based on BP neural network

The output layer of the neural network is the output fuzzy subset. The real output value can be obtained through a defuzzification process. This paper uses the centroid method to solve fuzzy subset. The calculation equation is as follows.

$$p = \sum_{k=1}^{5} p_k u_P(P_k) / \sum_{k=1}^{5} u_P(P_k) \qquad (1)$$

Where, p is barycenter, p_k is the membership degree of kth input layer, $u_P(P_k)$ is kth input value.

When the priority of each control loop is determined, in order to realize reasonable scheduling of networked control system, the system will determine the order of task execution based on the priority of each control loop. The fuzzy dynamic scheduling algorithm based on neural network takes into account the error and error change of each control loop in the system. This will not result in a control loop cannot be scheduled for its low priority. It is conducive to improve the overall performance of the networked control system.

D. Fuzzy controller with self-tuning scale factor

The fuzzy controller algorithm based on self-tuning scale factor is more efficient with better control effect [25]. It is a more effective method for the application of adaptive fuzzy control in real time control [26, 27]. For networked control system with resource constrained, affected by the network protocol, network bandwidth, packet loss and other factors, the dynamic characteristics of the controlled object will be changed, and also is influenced by various disturbances from the network [28]. Therefore, in the previous design of the basic fuzzy controller, once the scale factor is determined, if the external disturbance changes too large, the control performance of the system will be poor. In order to enhance the ability of the system to restrain the change of the external disturbance, this paper adopts the method of online self-tuning scale factor. Under the condition that k_e and $k_{\Delta e}$ are fixed, the general k_p increases. The corresponding control loop will get a bigger priority and occupy more network bandwidth. But k_p is too large, it will lead to the control loop occupy too much network resources, which make the performance of other control loops decreased, the system output will have too large overshoot and even jitter and divergence. Under certain conditions, the steady state of the system will be affected. k_p is too small will lead to the lower priority of the control loop. The control loop cannot get more network resources. The system output rising rate of corresponding control loop become small.

The structure of priority scheduler of networked control system based on fuzzy controller with self-tuning scale factor in this paper is as shown in Fig. 7.

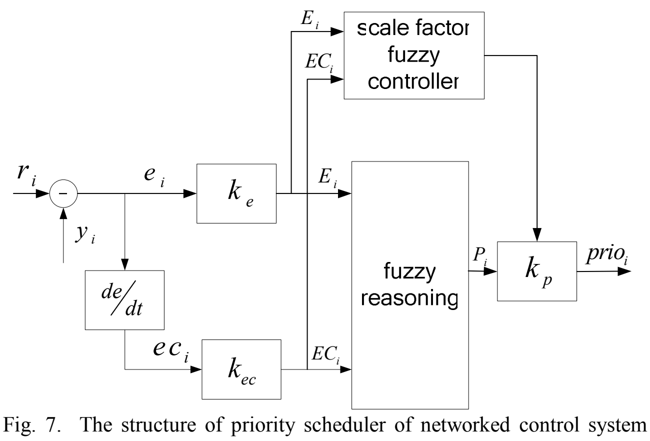

Fig. 7. The structure of priority scheduler of networked control system based on fuzzy controller with self-tuning scale factor

We can sum up a set of tuning rules for the parameter k_p which is described by fuzzy lingual. The tuning rules have the following form:

IF $E = A_i$ AND $Ec = B_j$

THEN $k_p = C_l \quad i, j = 1,2,\cdots,m; l = 1,2,\cdots,p$

Where A_i and B_j is the linguistic value of the corresponding domain, that is NB, NS, ZO, PS, PB. k_p is lingual variable of scale factor. C_l is the linguistic value of the corresponding domain. In this paper, lingual variable of C_l is VB, B, M, S. The fuzzy domain is as {1, 2, 3, 4, 5, 6, 7}. Table IV is the membership value of k_p.

TABLE IV

MEMBERSHIP VALUE OF k_p

	1	2	3	4	5	6	7
VB	0	0	0	0.1	0.4	0.8	1
B	0	0	0.2	0.7	1	0.7	0.2
M	0.4	0.8	1	0.8	0.4	0	0
S	1	0.8	0.5	0.2	0	0	0

According to the above scale factor tuning principle, we can get the tuning rules of k_p as shown in Table V. In real time operation, system can realize auto online tuning of parameters according to error e and error change ec. The final generated tuning query table of k_p is shown in Table VI.

TABLE V

THE TUNING RULES OF k_p

Ec	*E*				
	NB	NS	ZO	PS	PB
NB	VB	VB	B	M	S
NS	VB	B	M	S	B
ZO	VB	M	S	M	VB
PS	B	S	M	B	VB
PB	S	M	B	VB	VB

TABLE VI

THE TUNING QUERY TABLE OF k_p

Ec	*E*								
	-4	-3	-2	-1	0	1	2	3	4
-4	7	6	5	4	3	2	1	1	1
-3	7	5	4	3	2	1	1	1	1
-2	6	4	3	2	2	1	1	1	2
-1	5	3	2	2	1	1	1	2	3
0	4	3	2	2	1	2	2	3	4
1	3	2	1	1	1	2	2	3	5
2	2	1	1	1	2	2	3	4	6
3	1	1	1	1	2	3	4	5	7
4	1	1	1	2	3	4	5	6	7

IV. SIMULATION

A networked control system which contains three loops is used as the simulation object. The built simulation model is as shown in Fig. 8. The controlled object in each control loop is a DC motor, and its transfer function is as shown in (2).

$$G(s) = \frac{1000}{s(s+2)} \tag{2}$$

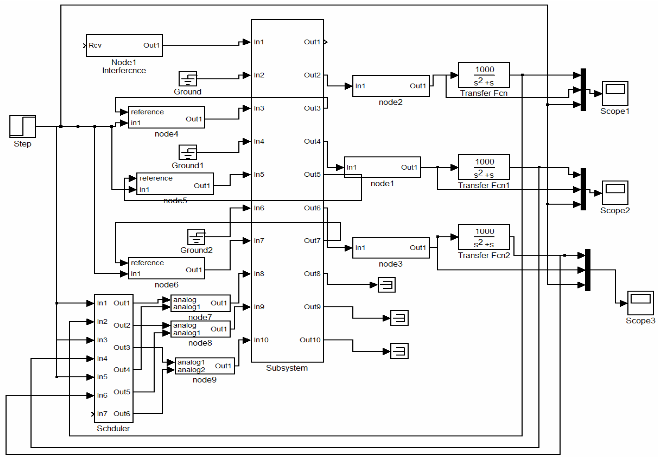

Fig. 8. Simulation model of fuzzy feedback scheduler with self-tuning scale factor

The research focus of this paper is the dynamic priority scheduling algorithm, so the controller uses digital PID control algorithm. The parameters of PID algorithm are as follows: proportion coefficient $K = 0.96$, differential coefficient $T_d = 0.094$, integral coefficient $T_i = 0.12$, differential gain $N = 10$. The simulation tool is True Time toolbox 1.5. The simulation network is CAN bus, packet size is 40bits, packet loss rate is 5%. The sampling period of three control loops is set as 10 ms. The input reference signal is a step signal. The simulation time is 3 seconds. In order to simulate the situation of network with resource constrained, an interference node random send data to network. In this paper, interference node occupies 20% network bandwidth. Considering the bandwidth constrained condition, the EDF scheduling algorithm in [17], the fuzzy feedback scheduling algorithm in [21] and fuzzy feedback scheduling with self-tuning scale factor algorithm in this paper are compared.

A. Output response comparison

Fig. 9 to Fig. 11 is the output response of three scheduling algorithms. It can be seen from Fig. 9, in the case of bandwidth limited, EDF scheduling algorithm adjust priority according to the deadline of task. So the output overshoot of three control loops is lager, and the stable time is very long. Fig. 10 is the output response curve of the fuzzy feedback scheduling algorithm. Fuzzy feedback scheduling algorithm uses control performance as reference value. The performance of loop 3 is greatly improved compared with the EDF scheduling algorithm. Fig. 11 is the output response curve of the fuzzy feedback scheduling with self-tuning scale factor algorithm. It can be seen from Fig. 11, the control performance of three control loops is improved than EDF and fuzzy feedback scheduling algorithm. The output overshoot is small, and stable time is shorter. The reason for the improvement of control performance is that the scale factor is dynamic adjusted according to error and error change rate. It will cause the scheduler to assign a higher priority to the control loop. Therefore, each loop has very good control performance.

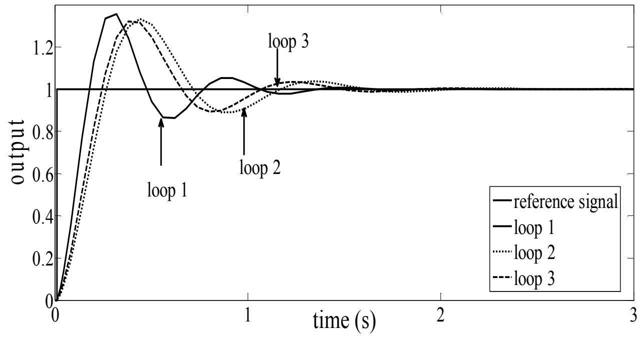

Fig. 9. Output response curve with EDF scheduling algorithm

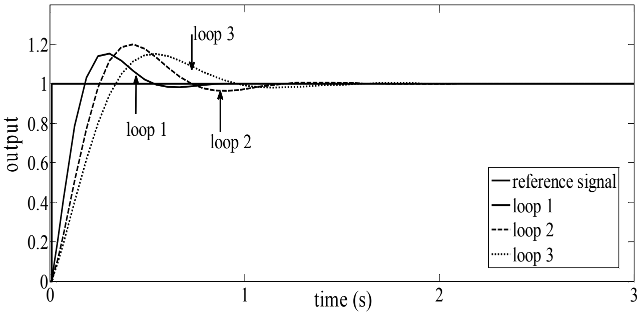

Fig. 10. Output response curve with fuzzy feedback scheduling algorithm

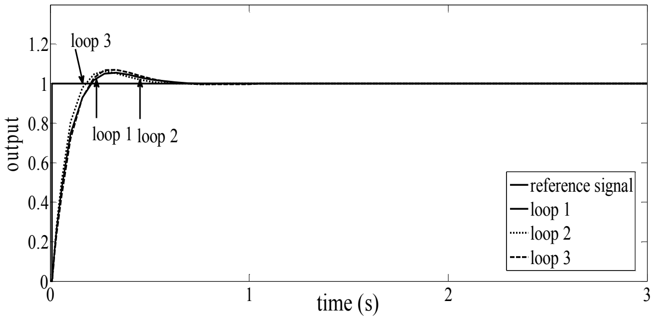

Fig. 11. Output response curve with scheduling algorithm in this paper

B. Data transmission delay

Fig. 12 to Fig. 14 is the network data transmission delay curve of three scheduling algorithms. It can be observed in Fig. 12, the network time delay of the 3 loops is mainly concentrated in 2.1 to 3.9 ms when EDF algorithm is adopted. Fig. 13 is the data transmission delay curve of fuzzy feedback scheduling algorithm, the network delay of three loops is mainly concentrated in 2.3 to 2.7 ms, only a few network delay is close to 4 ms. Fig. 14 is the data transmission delay curve of scheduling algorithm in this paper. It can be seen that the network delay of three loops are mainly concentrated in 1.8 to 2 ms. From the simulation results, we can note that the scheduling algorithm in this paper can reduce the data transmission conflict. Thus reduce the data transmission delay of three control loops.

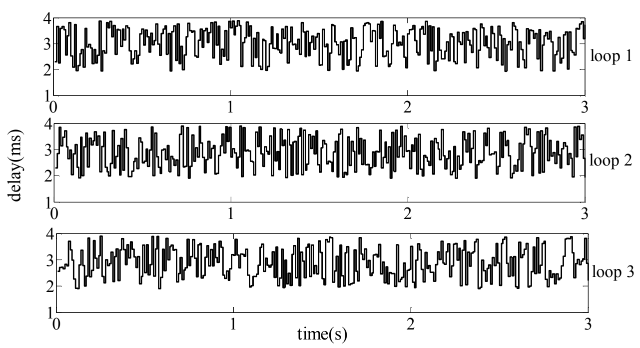

Fig. 12. Network data transmission delay with EDF scheduling algorithm

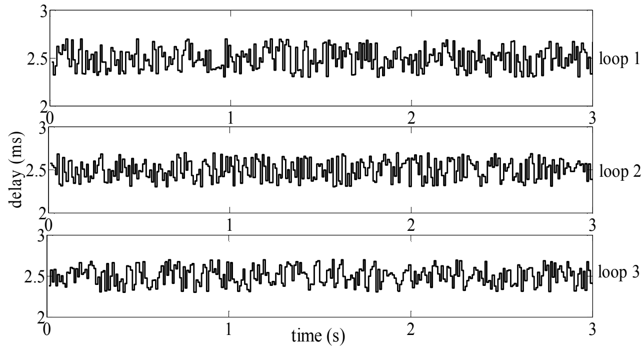

Fig. 13. Network data transmission delay with fuzzy feedback scheduling algorithm

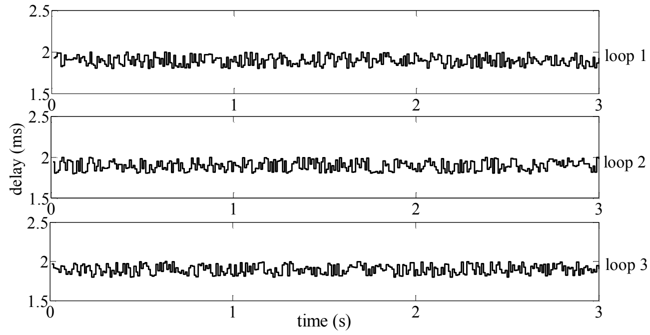

Fig. 14. Network data transmission delay with scheduling algorithm in this paper

C. IAE comparison

In this paper, integrated absolute error (IAE) value is used to measure the control performance of the control loops. The calculation equation for IAE is

$$IAE_i = \int_0^{\infty} | e(t) | \, dt \tag{3}$$

Equation (4) can be obtained by (3) after discretization,

$$IAE_i = \sum_k | e(k) | \bullet h_i \tag{4}$$

In order to better reflect the superiority of the priority allocation strategy in this paper, Fig. 15 to Fig. 17 is the change curve of the control performance of three scheduling algorithms. It can be observed in Fig. 15 to Fig. 17, the scheduling algorithm in this paper can obtain better IAE value compare with EDF and fuzzy feedback scheduling algorithm. At the same time, Table VII also shows the improvement of control performance of three control loops. The total IAE value of three control loops in the scheduling algorithm ins this paper is 0.196 less than EDF, and 0.068 less than fuzzy feedback scheduling algorithm. The scheduling algorithm in this paper is effective.

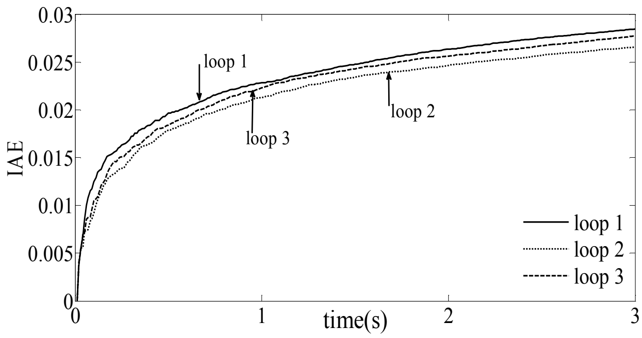

Fig. 15. The IAE value with EDF scheduling algorithm

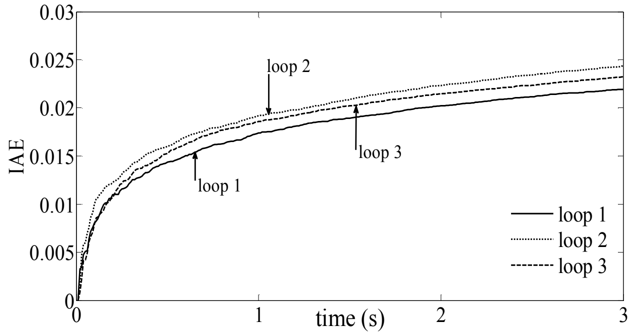

Fig. 16. The IAE value with fuzzy feedback scheduling algorithm

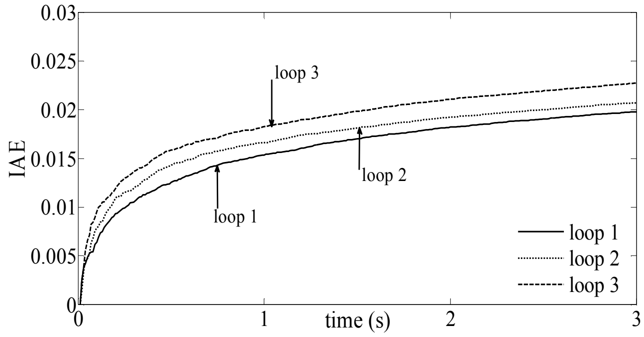

Fig. 17. The IAE value with scheduling algorithm in this paper

TABLE VII
THE IAE VALUE OF THREE SCHEDULING ALGORITHMS

Scheduling methods	EDF scheduling algorithm	Fuzzy feedback scheduling algorithm	Scheduling algorithm in this paper
Control loop 1	0.284	0.219	0.197
Control loop 2	0.266	0.243	0.205
Control loop 3	0.275	0.232	0.224
Total	0.825	0.694	0.626

D. Network utilization comparison

The network utilization is an important index to measure the performance of the network. In the case of limited network resources, the goal of the network scheduling algorithm is to make the network utilization as low as possible, so as to reduce the probability of data conflict and congestion and create the opportunity for other nodes to send out the emergency message. This paper will give the simulation results of network utilization of EDF, fuzzy feedback and priority scheduling method in this paper.

Network utilization is defined as follows:

$$U = U_1 + U_2 + \cdots + U_N = \sum_{i=1}^{N} \frac{C_i}{T_i} \quad (5)$$

Where, U is network utilization of networked control system, C_i is data transmission time of *ith* loop, T_i is the sampling period of *ith* loop. In the simulation of this paper, the sampling time of three loops is constant, so the network utilization is affected by the data transmission time. Fig. 18 gives the network utilization of EDF. Fig, 19 gives the network utilization of fuzzy feedback and Fig. 20 gives the network utilization of fuzzy feedback with self-tuning scale factor in this paper.

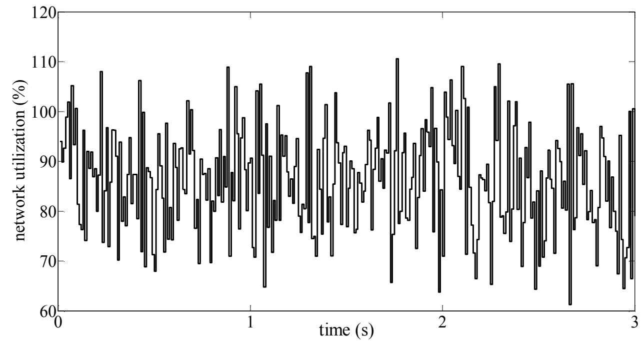

Fig. 18. Network utilization with EDF scheduling algorithm

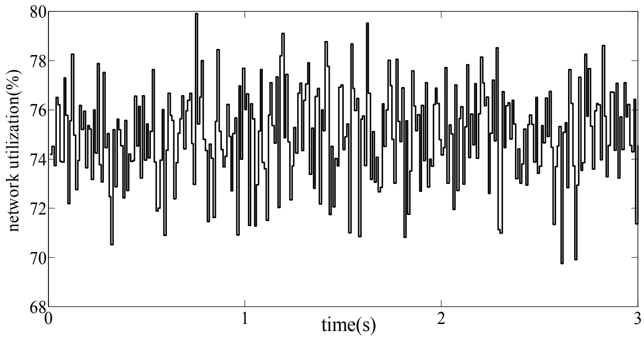

Fig. 19. Network utilization with fuzzy feedback scheduling algorithm

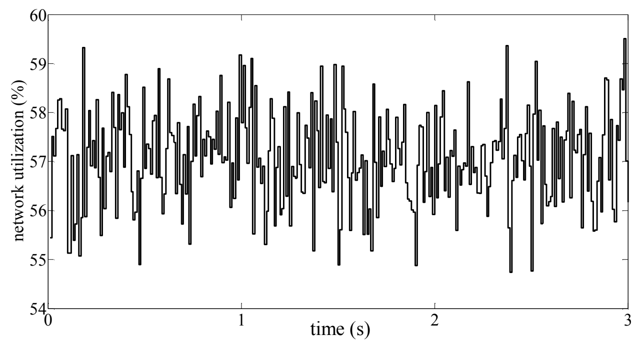

Fig. 20. Network utilization with scheduling algorithm in this paper

It can be observed from Fig. 18 to Fig. 20, the network utilization with EDF scheduling algorithm is very high, sometimes even greater than 100%, which shows that in this case the network cannot be scheduled; the system performance will be greatly affected. Compared with fuzzy feedback scheduling algorithm, the proposed scheduling algorithm in this paper will occupy less network bandwidth. The proposed priority scheduling algorithm can save more network bandwidth, and create more resources to other network nodes.

V. CONCLUSION

This paper proposes a priority scheduling algorithm of networked control system based on fuzzy controller with self-tuning scale factor. Under the conditions of network bandwidth constrained, considering system output error, error change and self-tuning scale factor, the priority of each control loop is adjusted dynamically. The priority of each loop is suitable for the actual running state of the whole control system. The simulation model is built by True time toolbox. The simulation experiments are performed and compared with EDF and fuzzy feedback scheduling algorithm. The simulation results show that the proposed scheduling algorithm can improve the system output performance, reduce the data transmission delay, integral absolute error of the control loop and network utilization of the system.

The future research work of this paper is combined scheduling algorithm in this paper with variable sampling period algorithm. The co-design of control and scheduling is realized. The performance of the system will be further improved.

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