Research on Improved Earliest Deadline First Scheduling Strategy of Networked Control System

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Abstract: How to design effective scheduling strategy, improve the performance of tasks in networked control system, optimize the quality of data transmission, and improve the adaptability of tasks with dynamic attributes is of great significance. Considering that the overall performance of networked control system is closely related to the time attribute of transmission task and channel environment, this paper improves the classic earliest deadline first scheduling strategy. Starting from the schedulable condition, the dynamic time interval of the task is accurately processed, and the distribution function of the schedulable condition is obtained by using the distribution function of each attribute. The exact value of the schedulable variable meeting the requirements is determined, so as to obtain the accurate execution time and cycle value of the task attribute. The simulation experiment is carried out on the TrueTime platform. In the simulation, the scheduling effect of the three loop networked control system is compared under the conditions of an ideal environment, different packet loss rate and interference rate, dynamic change of execution time and cycle. The results show that the improved earliest deadline first scheduling strategy overcomes the disadvantage of system performance degradation caused by the standard earliest deadline first scheduling strategy. This scheduling strategy improves the output quality of the system and improves the adaptability of the system to packet loss and interference factors.

Keywords: networked control system, scheduling, earliest deadline first, packet loss, interference.

1. INTRODUCTION

1.1 Research background

With the rapid development of communication means and computer related technology, network technology is becoming more and more popular, resulting in a very wide range of applications and great influence of the network. Traditional control technology, such as distributed control or centralized control, is difficult to meet the requirements of social development and system control. With the increasing complexity of control technology, the guarantee of control effectiveness has become an inevitable factor in the introduction of a control system into network application. Networked control system (NCS) is through the introduction of information network, so that a large number of control laws can directly act on the controlled object through the communication network, and can quickly feedback back to the control center through the network, to achieve the goal of data exchange and control accurate and timely (Gautam et al., 2021; Wang et al., 2016). The basic structure of NCS is shown in Fig. 1, which has the advantages of high reliability, good flexibility, low cost and distributed processing (Ferrari et al., 2021).

In a NCS, the system performance not only depends on the choice of control strategy, but also has a close relationship with the allocation of resources in the network. Therefore, scheduling strategy plays an important role in performance control of NCS (Tian et al., 2018). In this paper, the scheduling strategy in NCS is studied.

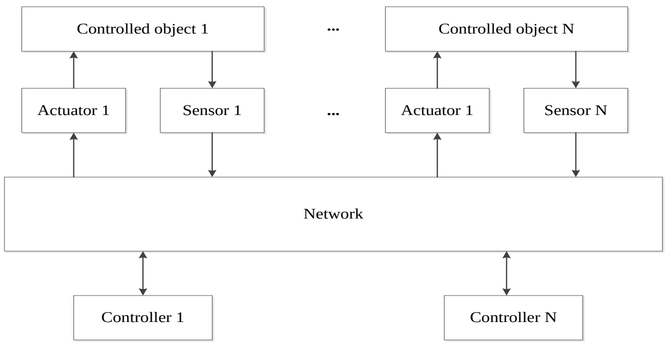

Fig. 1. The basic structure of NCS.

1.2 Literature review

In recent years, many scholars have carried out corresponding research on the scheduling problem of NCS, and achieved some results. The most classic scheduling strategy of NCS is static scheduling strategy. Among the static scheduling strategies, the typical ones are rate monotonic (RM) strategy (Gao et al., 2012), fix priority (FP) strategy (Kim et al., 2014), and so forth. But there are many shortcomings in static scheduling strategy. (a) The scheduling efficiency of aperiodic information is not high. Static scheduling simply regards all information as periodic tasks, and defines the period of aperiodic information with the minimum arrival time interval. Therefore, the static scheduling strategy has some idealism. (b) Lack of adaptability to change. The addition and deletion of nodes become more complex, and if the key nodes leave the system by mistake, the operation of the whole system must be stopped, resulting in the lack of universal adaptability and flexibility of the system. (c) Low resource utilization. It is necessary to determine the system's operation cycle and the worst-case allocation of resources in advance, which will inevitably lead to the waste of resources in the system.

Due to the deficiency of static scheduling strategy, dynamic scheduling strategy has been widely used. Compared with the static scheduling strategy, which needs to be set before execution and cannot be changed after execution, its most obvious advantage is that it has good adaptability to system changes, and can make more full use of channel resources. Typical dynamic scheduling strategies include earliest deadline first (EDF) scheduling strategy (Kalaivani and Kalaiarasi, 2019), maximum error first try once discard (MEF-TOD) scheduling strategy (Zhou et al., 2019), etc.

In recent years, many scholars have proposed some new scheduling strategies for NCS based on dynamic scheduling theory. In the study, in order to improve the performance of the NCS, a deadband feedback-based scheduling approach for the NCS with a variable sampling period is proposed. The simulation results show that the proposed scheduling approach can improve output control performance of the system, reduce integral absolute error value of the control loops, and improve network utilization (Tian, 2021). The authors proposed a modified media allocating model of multifunction vehicle bus for the train NCS. The proposed collaborative design strategy can minimize the network resource occupancy rate of the subsystem. The numerical simulation and experimental tests illustrate the effectiveness of the strategy (Yan et al., 2021). In their study (Zhao and Ji, 2021), a novel model-dependent scheduling scheme is proposed for the networked control system with time-delay, disturbance, and medium access constraints. The illustrative examples are given to demonstrate the affectivity of the proposed scheduling method and the co-design scheme. By using a gain scheduler within the packet-based control framework and fitting the delay-dependent gains into a time-delay system model, a less conservative self-triggered approach is proposed to determine the sampling update (Zhao et al., 2021). The simulation results show the proposed approach reduces greatly the communication usage while maintaining satisfactory control performance.

In their study (Fan et al., 2020), a dual-way scheduling algorithm is finally proposed for distributed NCS with different types of transmitted data packets. Experiments are conducted on a remote teaching platform to verify the effectiveness of the proposed dual-way scheduling mechanism. In their study (Kundu and Quevedo, 2020), a scheduling method under which global asymptotic stability of each plant in the NCS is proposed. The simulation results verify the feasibility of the proposed scheduling strategy. In the literature (Yan et al., 2020), a dynamic bandwidth resource allocation model of the overall control system for optimal performance is proposed. The numerical simulations are performed for variety of system parameters and NCS set-ups to strengthen the stability.

From the above research results, the scheduling strategy of NCS has made some progress. However, many scheduling strategies are too complex, although they can achieve good performance in simulations; the complexity of the algorithm greatly limits the application of these scheduling strategies in practice. Furthermore, these scheduling strategies have many assumptions for network data transmission and controlled objects. If these conditions are not met, the scheduling effect will be greatly reduced. As the most classic dynamic scheduling strategy, EDF has many advantages. The most important thing is that EDF is the optimal dynamic scheduling strategy. When the dynamic scheduling strategy is feasible, EDF scheduling must be satisfied, and theoretically, the network utilization can reach 100%. Therefore, improving the traditional EDF scheduling strategy is more important for its practical application.

1.3 Main contributions

Considering that the overall performance of NCS is closely related to the time attribute of transmission task and channel environment. This paper improves the classic EDF strategy. The main contributions are as follows.

1. Based on the schedulable condition, the dynamic time interval of the task is processed accurately, and the distribution function of the schedulable condition is obtained by using the distribution function of each attribute.

2. According to the two rules of possibility and necessity, the precise value of schedulable variable is determined, and the exact execution time and cycle value of task attribute are obtained.

3. In the simulation, the task transmission performance under different packet loss rate and interference rate is verified. The simulation results are closer to the actual situation.

The rest of this paper is organized as following. Section 2 designs improved EDF scheduling strategy. The simulation results are given in Section 3. The conclusions and future work are presented in Section 4.

2. IMPROVED EDF SCHEDULING STRATEGY

In the actual implementation of NCS, there are many influencing factors, such as delay, packet loss, preemption and so on, which will seriously affect the stability of the system. In the theoretical task transmission, the traditional scheduling strategy is based on the ideal conditions, such as the execution time of each task transmission is completely independent, and it is assumed that all the network communication delays are predictable in the whole working process. However, in practice, the execution time and processing time of tasks are closely related to the processor operation of the system. Under full load and light load, due to the different bandwidth, the actual execution time is also different. At the same time, interference, clock accuracy and other factors may also affect the attributes of tasks in the system. These factors bring changes to the original ideal system. In this paper, the network data transmission is improved, and the preemptive EDF scheduling algorithm with time precision processing is used to solve the problem of attribute dynamic change in the system work. Through certain constraints, the dynamic change is transformed into determination, and the determined attributes are used for scheduling, so that the system can get a satisfactory scheduling effect, and the stability is guaranteed.

2.1 Processing of dynamic change of task execution time

Considering that the execution time of tasks in NCS is dynamic, this paper analyzes the basic EDF scheduling strategy from two aspects: the scheduling condition and the scheduling strategy.

2.1.1 Schedulable condition

In the classical EDF scheduling algorithm, the schedulability of the system needs to meet the following conditions (Sharma et al., 2020).

$$U = \sum_{i=1}^{n} \frac{c_i}{h_i} \le 1, (i = 1, 2, \cdots, n) \quad (1)$$

where c_i is the execution time of the task, h_i is cycle of task, n is the number of tasks. In the standard EDF scheduling algorithm, the execution time c_i is an accurate value. In this paper, the task execution time of the research object is changed to a non-fixed value, that is, dynamic. Therefore, the Eq. (1) satisfying the scheduling condition is modified adaptively, that is, a variable W is used to replace U in the Eq. (1).

Two condition parameters are used to explain this W, possibility condition $M(W \le 1)$ and necessity condition $N(W \le 1)$. And define a distribution function about W, denoted as $\varphi_w(w)$, to constrain and determine the above two parameters. Suppose a transmission task T_i, whose execution time is c_i, a distribution function $\varphi_w(w)$ related to time variable is defined. The value of the distribution function is related to the dynamic variable time $c_1, c_2, \cdots, c_n$, and its distribution function is as follows.

$$\varphi_w(w) = \min_{t_1, t_2, \cdots, t_n} \left\{ \varphi_{c_1}(t_1), \varphi_{c_2}(t_2), \cdots, \varphi_{c_n}(t_n) \right\} \quad (2)$$
$$s.t. w = \sum \frac{t_i}{h_i}$$

where w is an independent variable of W. The function $\min(\cdots)$ is the minimum value of the distribution function of the schedulable variable W when all execution time c_i has the same distribution function value. The two conditional parameters M and N satisfy the following conditions.

$$M(W \le 1) = Sup(\varphi_w(w)), w \le 1 \quad (3)$$

$$N(W \le 1) = 1 - M(W > 1) = 1 - Sup(\varphi_w(w)), w \le 1 \quad (4)$$

where $Sup()$ is the minimum upper bound function, which indicates the maximum value of variable w when the distribution function $\varphi_w(w)$ of W takes a certain value.

2.1.2 Scheduling strategy

The basis of providing a feasible scheduling strategy for the transmission of system tasks is to select the best scheme among all feasible schemes. On this basis, when multiple tasks are transmitted in the system, the task can have a higher possibility of transmission. The dynamic execution time of tasks mostly changes in an interval. There are two special endpoint time values in the task distribution function, namely the minimum and maximum execution time. Corresponding to these two cases, in the case of choosing different time values, there are two different scheduling strategies. The dynamic execution time is replaced by the maximum or minimum endpoint time, which is the precise processing of the dynamic execution time attribute. The improved EDF scheduling strategy in this paper supplements and adjusts the classical EDF strategy, accurately calculates the values of possibility conditions and necessity conditions under schedulable conditions, and calculates the accurate time values of all tasks in execution, so as to achieve the purpose of accurate processing of dynamic time. In the scheduling of multiple tasks, the schedulable condition W depends on the feasibility condition and necessity condition.

1. When the value of $\varphi_w(w)$ is the maximum, w is greater than 1. In the current situation, the possibility and necessity of scheduling need to be met $0 < M(W \le 1) = \alpha < 1$, $N(W \le 1) = 0$. At this time, it is considered that the task execution time in the current transmission is close to the minimum. In this case, each task with the minimum execution time can guarantee that the scheduling strategy has the possibility of α. Meantime, corresponding to the possibility value, that is, under the condition of $\varphi_{c_i}(t)$ is α, the execution time of each task corresponds to two endpoint time values, and the smaller value is taken as the accurate time. In addition, if the feasibility condition is $M(W \le 1) = 0$, the transmission process is considered to be non-schedulable.

2. When the value of $\varphi_w(w)$ is the maximum, the independent variable w is less than 1. In the current situation, the possibility and necessity conditions of scheduling should be met as $M(W \le 1) = 1$ and $0 < N(W \le 1) = 1 - \beta \le 1$. At this time, it is considered that the task execution time in the current transmission is close to the maximum. In this case, the maximum execution time of each task can ensure the necessity of scheduling $1-\beta$. At the same time, corresponding to the possibility value, the two endpoint time values corresponding to the execution time of each task under the condition of $\varphi_{c_i}(t) = \beta$, take the larger value as the accurate time. In addition, if the necessary condition $N(W \le 1) = 1$ is satisfied, the transmission process is considered schedulable. The improved EDF scheduling strategy selects a larger execution time for each task under this condition, and all tasks can be transferred and completed before the deadline.

3. When the value of $\varphi_w(w)$ is the maximum, the independent variable w is equal to 1. In the current situation, the conditions of scheduling possibility and necessity are $M(W \le 1)=1$ and $N(W \le 1)=0$. The time corresponding to $\varphi_{c_i}(t)=1$ is the exact execution time of each task.

The following is an example of the process of precise processing of task execution time. Suppose there are three tasks in the NCS, T_1, T_2 and T_3, their task cycles are 0.01, 0.02 and 0.03. The execution time is 0.004, 0.005 and 0.006. And the fluctuation range is set to 0.001, which indicates that the execution time changes dynamically in the interval. According to the principle that the maximum and minimum values are accurate in the scheduling strategy, a more appropriate triangular distribution function is used for processing. Fig. 2 shows the distribution function diagram of each task.

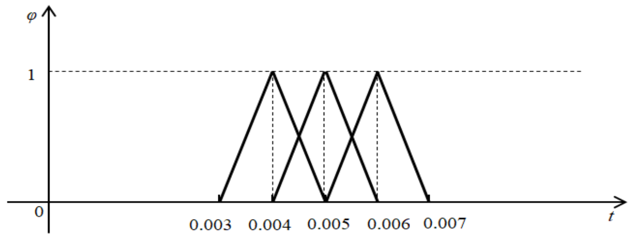

Fig. 2. Distribution function of execution time of each task under dynamic execution time.

The distribution function of *W* can be obtained by calculating the formula of schedulable variable, as shown in Fig. 3. According to the second case of scheduling strategy, $M(W \le 1)=1$, $N(W \le 1)=1\text{-}\beta=9/11$ and $\beta=2/11$ can be obtained. In this case, the precise value of execution time is taken as $N(W \le 1)=1\text{-}\beta=9/11$, The maximum value of the distribution function of each task is used as the precise time, namely $c_1=0.0048$, $c_2=0.0058$ and $c_3=0.0068$. Then, the execution time of dynamic change is processed.

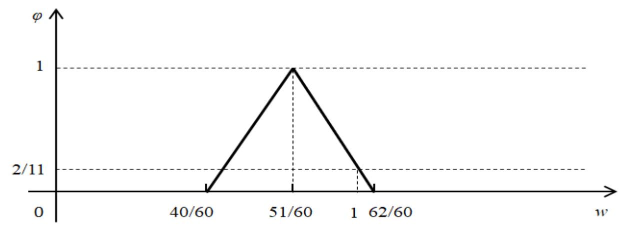

Fig. 3. Distribution function of schedulable variable *W* under dynamic change of execution time.

2.2 Processing with uncertain execution time and period

Define a distribution function $\varphi_{h_i}(t)$ about sampling period, and set an intermediate attribute variable to represent the ratio of task execution time and task cycle, which is expressed as $p_i = c_i / h_i$. The distribution function of p_i is defined as

$$\varphi_{p_i}(p)=\varphi_{c_i/h_i}(p)=\min_{t_2>0,t_1/t_2=p}\left(\varphi_{c_i}(t_1),\varphi_{h_i}(t_2)\right) \tag{5}$$

Then, the distribution function of schedulable variable *W* is obtained

$$\varphi_w(w)=\min_{z_1,z_2,\cdots,z_n}\left\{\varphi_{p_1}(z_1),\varphi_{p_2}(z_2),\cdots,\varphi_{p_n}(z_n)\right\} \quad s.t. w=\sum z_i \tag{6}$$

Similarly, a brief example is given to illustrate the process of the precision processing. Suppose the system has three tasks, T_1, T_2 and T_3, and their execution time and fluctuation range are 0.004 ± 0.001, 0.006 ± 0.001, and 0.007 ± 0.001. The cycle time and fluctuation range are 0.01 ± 0.001, 0.02 ± 0.002 and 0.03 ± 0.003. The triangle distribution is selected as the distribution function of task time according to the principle of accurate maximum and minimum value in scheduling strategy. Fig. 4 shows the distribution function of each task.

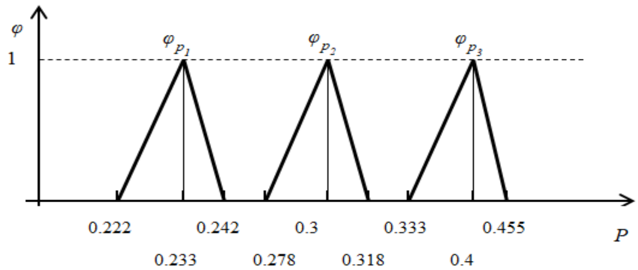

Fig. 4. The distribution function of *p* under dynamic changes of both execution time and cycle.

The distribution function of schedulable variable *W* can be obtained by calculation, as shown in Fig. 5. Obviously, when the value of distribution function is the maximum value of 1, the corresponding value of independent variable *w* is less than 1. $M(W \le 1)=1$, $N(W \le 1)=1$, and $\beta=0.405$. Let $\varphi_{c_i}(t)=\beta=0.405$, the maximum value of the distribution function of each task is taken as the precise time. We can get the execution time of three tasks as 0.0046, 0.0066 and 0.0082. The cycle times are $h_1=0.0106$, $h_2=0.0212$ and $h_3=0.0318$.

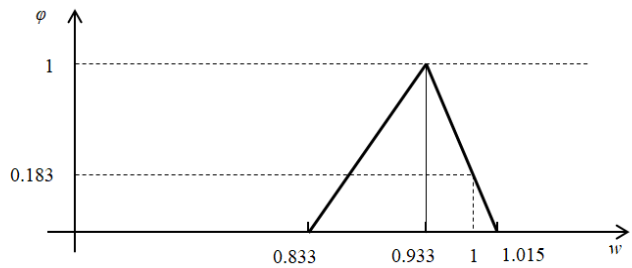

Fig. 5. Distribution function of schedulable variable *W* under changes of both execution time and cycle.

3. SIMULATIONS

In this paper, TrueTime is chosen as the simulation platform. Multi loop NCS is adopted. The whole system consists of a network communication module, sensors, controller, actuators and interference nodes. The driving mode of the sensor is clock driven mode. The data is sampled periodically and sent to the controller through the network. The controller and actuators are event driven mode. In the application layer, the transmission tasks executed by each sensor are scheduled, and the transmission order is allocated through a certain scheduling strategy, so that the task packet transmission of the whole network can be carried out orderly and stably. The following transfer function model is selected for the controlled objects of the three loops.

$$G(s) = \frac{1000}{s^2 + s} \tag{7}$$

Because the main problem of this paper is the scheduling strategy of the NCS, the classic PID controller is adopted. The parameters of PID controller are as follows $K = 0.95$, $T_i = 0.07$, $T_d = 0.05$, $N = 100$ and $h = 0.01$. The sampling periods of the three loops are 0.04s, 0.05s, and 0.07s. CAN network is chosen as the communication network in the simulation.

According to the above dynamic example of execution time, the classic EDF scheduling strategy and the improved EDF scheduling strategy are used for task transmission. Under this dynamic condition, considering the influence of packet loss and interference in the network channel, the transmission of tasks and the scheduling of each execution loop in the network are observed. In NCS, there are many nodes, which will send packets irrelevant to the control task. These data packets may be interference or normal communication data between other nodes, but they will affect the current normal control tasks. The existing interference will occupy the bandwidth resources of the network, increase the packet transmission delay, increase the probability of data conflict, and greatly affect the control performance of the control loop. In the simulation, the concept of interference rate is introduced to represent these other data packets that have nothing to do with the control task. Interference rate refers to the proportion of bandwidth occupied by interfering nodes in NCS, which can be used to realize the condition of bandwidth limitation. In the implementation, these network interference nodes randomly send data packets to the network, and the proportion of the network bandwidth occupied by the sent data packets is the interference rate. In order to discuss the output response curve of network transmission and the scheduling of each loop task under the influence of interference and packet loss, the following simulation schemes are selected.

3.1 Simulation scheme I: packet loss rate is 0, interference rate is 0

This simulation scheme is the ideal state of the NCS, there is no interference rate and packet loss rate. The relevant simulation results are shown in Fig. 6. The simulation results show that the standard EDF scheduling strategy has poor scheduling effect on the premise of no interference and packet loss in the NCS. In contrast, under this condition, the output curve fluctuation of each task in NCS is significantly reduced after the improved EDF scheduling strategy accurately processes the event execution time. During the scheduling period, the task can be transmitted in a certain order. The network task scheduling performance is better, the data transmission is ideal, and the system is more stable.

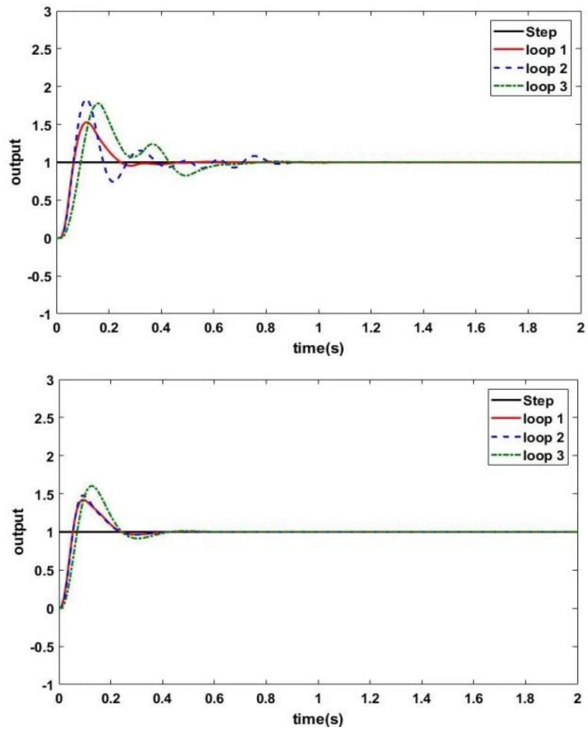

Fig. 6. Output under packet loss rate 0 and interference rate 0 (top: EDF; bottom: improved EDF).

3.2 Simulation scheme II: interference rate is not 0, packet loss rate is 0

When there is interference in the system, the output and scheduling of the system will be affected to a certain extent, which cannot be ignored. In the simulation, the scheduling of the system with different interference rate is studied. Fig. 7 shows the output response curves of the three loops under standard EDF and improved EDF scheduling strategies when interference rate is 0.2 and packet loss rate is 0. It can be seen from the comparison in Fig. 7 that under the traditional EDF scheduling strategy, the system output oscillates, and it takes a certain time to reach a stable state. The improved EDF scheduling strategy can suppress the system oscillation. After improving the EDF scheduling strategy, the task scheduling situation maintains a relatively good level.

The interference rate of the system is increased to 0.3, Fig. 8 shows the output response curves of the three loops under standard EDF and improved EDF scheduling strategies. Through the comparison of simulation results in Fig. 8, it can be seen that the increase of transmission channel interference makes the output quality of the traditional EDF scheduling strategy decline significantly. Although the overshoot gradually narrows and tends to be stable, the adjustment time becomes longer and the transmission performance of the system decreases. Under the control of the improved EDF scheduling strategy, the system output oscillation is significantly suppressed, the invalid priority competition under the dynamic execution time is reduced, and the system output is significantly improved. From the scheduling of each task, the execution of each task has been better allocated, and the task transmission is still controllable.

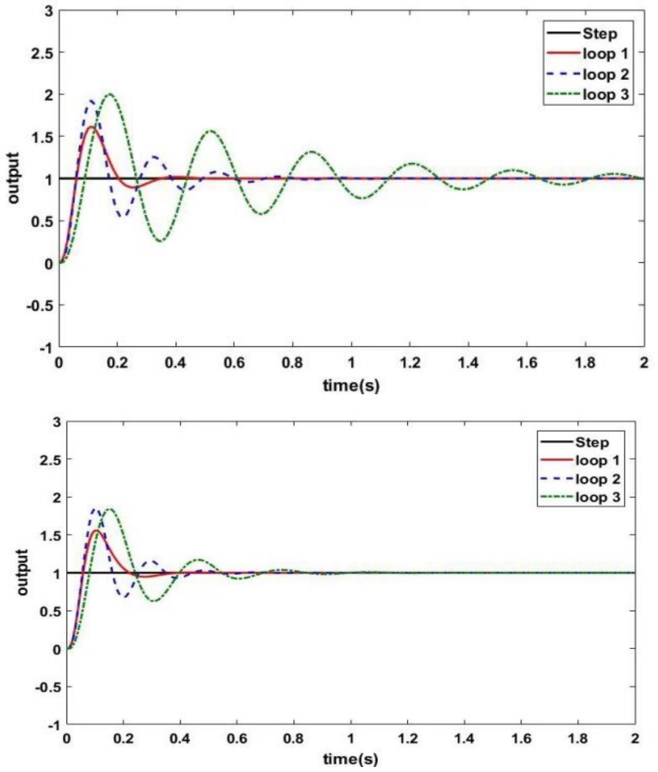

Fig. 7. Output under interference rate 0.2 and packet loss 0 (top: EDF; bottom: improved EDF).

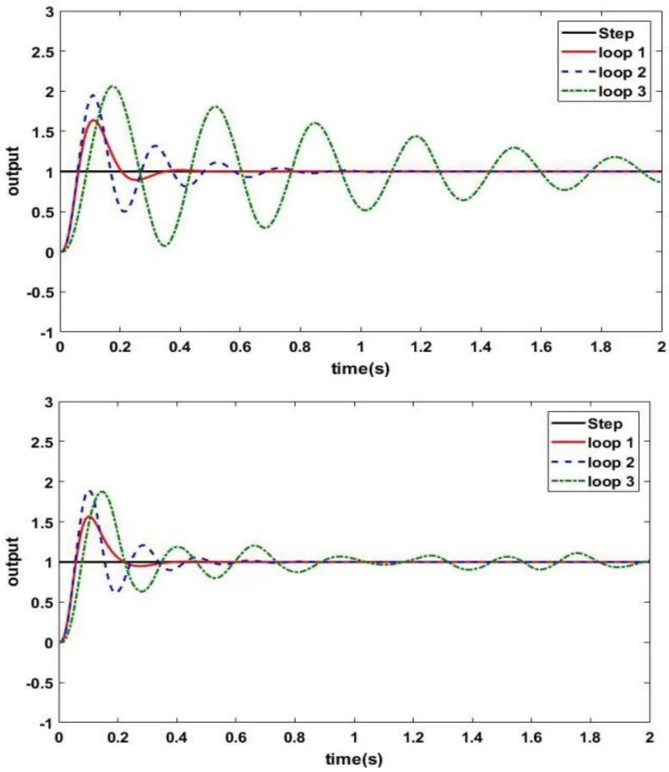

Fig. 8. Output under interference rate 0.3 and packet loss 0 (top: EDF; bottom: improved EDF).

The interference rate of the system is increased to 0.4, the corresponding simulation results are shown in the next Fig. 9.

It can be seen that under the traditional EDF scheduling strategy, the transmission quality of tasks decreases sharply, the oscillation of a single loop becomes uncontrollable, the scheduling effect becomes worse, and the system gradually loses stability. The improved EDF strategy solves the problem of priority competition confusion caused by uncertain time attributes, and significantly improves the tolerance of the control loop to external interference factors. Under the same interference, the transmission results after accurate processing still oscillates, but remain in the same controllable range. Task scheduling and system stability are significantly improved.

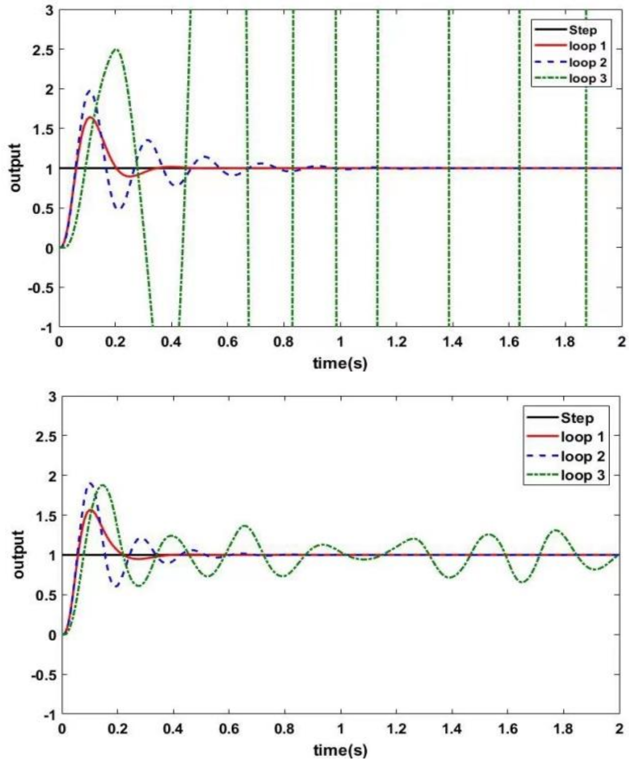

Fig. 9. Output under interference 0.4 and packet loss 0 (top: EDF; bottom: improved EDF).

3.3 Simulation scheme III: packet loss rate is not 0, interference rate is 0

In this simulation scheme, packet loss rate is not 0, interference rate is 0. In this case, there is no network interference. Network task conflict, channel preemption and other situations will lead to packet loss. The packet loss rate is related to channel load and congestion. Therefore, packet loss rate can influence the performance of NCS.

Fig. 10 shows the output responses of the standard EDF scheduling strategy and the improved EDF scheduling strategy when there is no interference but the packet loss rate is 0.1. Compared with the system output and task scheduling before the improvement, it can be seen that the improved EDF scheduling strategy makes the output scheduling controllable under the condition of low packet loss level. Under the improved EDF strategy, the output oscillation of the system is improved and the system stability is relatively good.

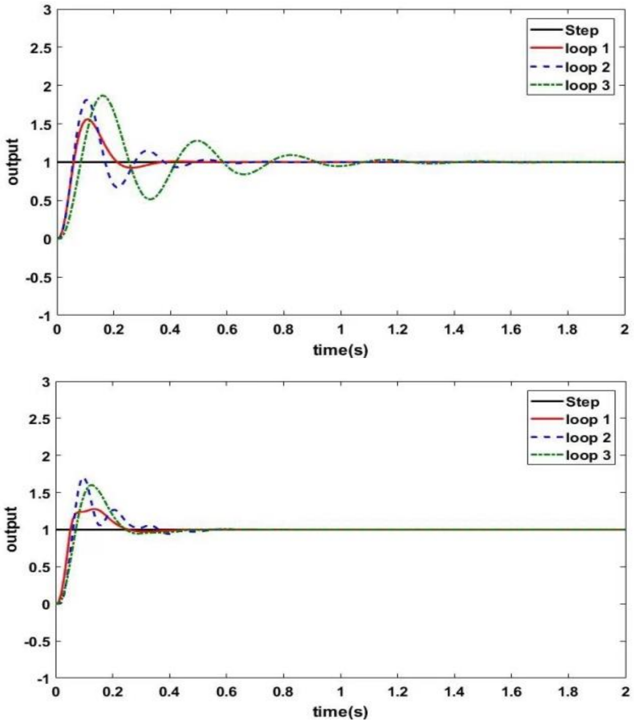

Figure 10. Output under packet loss rate 0.1 and interference rate 0 (top: EDF; bottom: improved EDF).

The packet loss rate is increased to 0.15, and the scheduling effect of the two scheduling strategies is compared. Fig. 11 shows the output responses of the standard EDF scheduling strategy and the improved EDF scheduling strategy when there is no interference but the packet loss rate is 0.15.

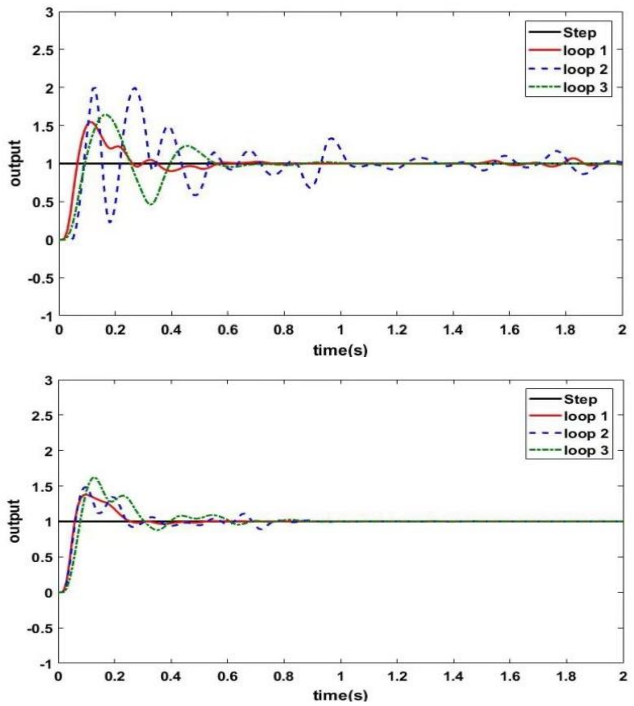

Fig. 11. Output under packet loss rate 0.15 and interference rate 0 (top: EDF; bottom: improved EDF).

From the simulation results, it can be seen that under the traditional EDF scheduling strategy, the amplitude of the output oscillation of the system begins to increase, the time from the output to the steady state becomes longer, the system performance begins to decline, and the scheduling quality also gradually decreases. Because of dealing with the uncertainty execution time, the improved EDF scheduling strategy reduces the factors that have adverse effects on the system performance, so the output performance is significantly improved, and the oscillation is reduced. When the task is transmitted in the network, the network resources are used more effectively, and the scheduling effect is restored to a certain extent. The stability of the whole system is also improved.

Furthermore, the packet loss rate is increased to 0.2. Similarly, the simulation results are shown in the Fig. 12. The simulation results show that under the standard EDF scheduling strategy, due to the increase of packet loss rate, the transmission quality of system tasks decreases sharply, and the amplitude of output oscillation of multiple tasks is too large and unstable. At the same time, it can be seen that compared with the network interference, the impact of task packet loss rate on system transmission is more obvious. When the packet loss rate is too high, the system will lose balance. Under the improved EDF scheduling strategy, the system can accept a certain proportion of the packet loss rate, increase the fault tolerance of the transmission process, improve the system performance and transmission quality, and improve the scheduling ability of each task loop.

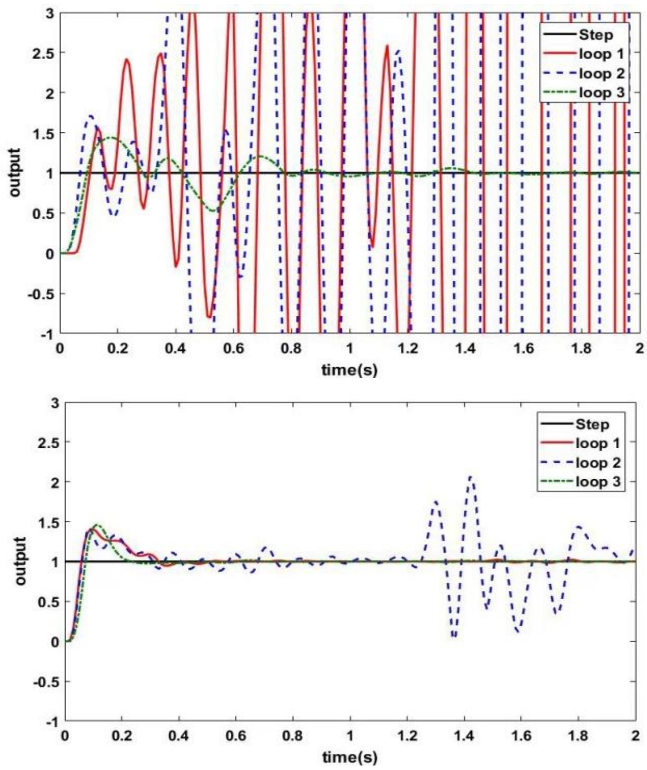

Fig. 12. Output under packet loss rate 0.2 and interference rate 0 (top: EDF; bottom: improved EDF).

3.4 Simulation scheme IV: packet loss rate is not 0, interference rate is not 0

In this simulation scheme, the packet loss rate and interference rate exist at the same time to verify whether the scheduling strategy is effective. The packet loss rate is set as

0.15 and the interference rate is set as 0.3. The relevant simulation results are shown in Fig. 13. Under the traditional EDF scheduling strategy, due to the simultaneous packet loss and interference factors in NCS and the dynamic change of execution time, when the transmission of each task is occupied by a large amount of resources by external factors, the network competition is more intense. In contrast, the improved EDF scheduling strategy enables the orderly transmission of tasks, enhances the tolerance of the system to adverse factors, and improves the quality of data transmission and system stability.

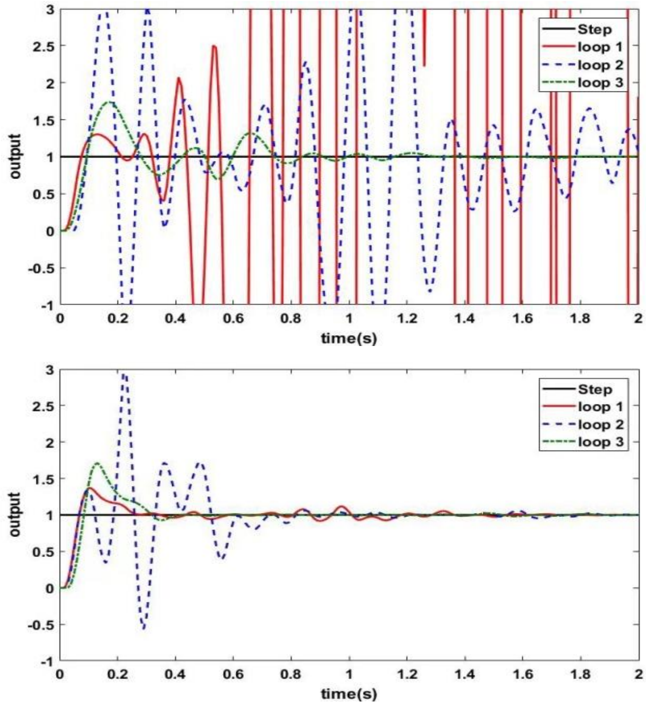

Fig. 13. Output under packet loss rate 0.15 and interference rate 0.3 (top: EDF; bottom: improved EDF).

3.5 Simulation scheme V: execution time and cycle change dynamically

The above four simulation schemes start from the packet loss and interference that affect the NCS, and analyze the influence of various factors on the transmission and stability of the system. The simulation results show that the improved EDF scheduling strategy can effectively improve the transmission efficiency and system stability of multi task NCS, and improve the adaptability of the system to other adverse factors. The performance of NCS is analyzed when the execution time and cycle change dynamically. Since the impact of packet loss and interference factors on this situation is basically the same as the previous analysis, it will not be discussed repeatedly. Here, this paper only analyzes the output and scheduling of each task in NCS without interference and packet loss. The output response of the three loops under the standard EDF and the improved EDF scheduling strategy is shown in Fig. 14. From the comparison of simulation results, it can be seen that when the execution time and periodic attributes of tasks change dynamically, the standard EDF scheduling strategy makes the scheduling time of each task in the network unable to be determined due to the competition rules, and the task transmission cannot be carried out orderly, resulting in the poor schedulability of network tasks. It makes the task unable to complete the normal execution, the time for the system to reach the stable state becomes longer, and the transmission quality of the whole network control system is also seriously reduced. After using the improved EDF scheduling strategy, the time attribute of each task is determined, and the priority determination is relatively more effective. The improved EDF scheduling strategy can improve the effect of data transmission in the control loop and ensure the stability of the system.

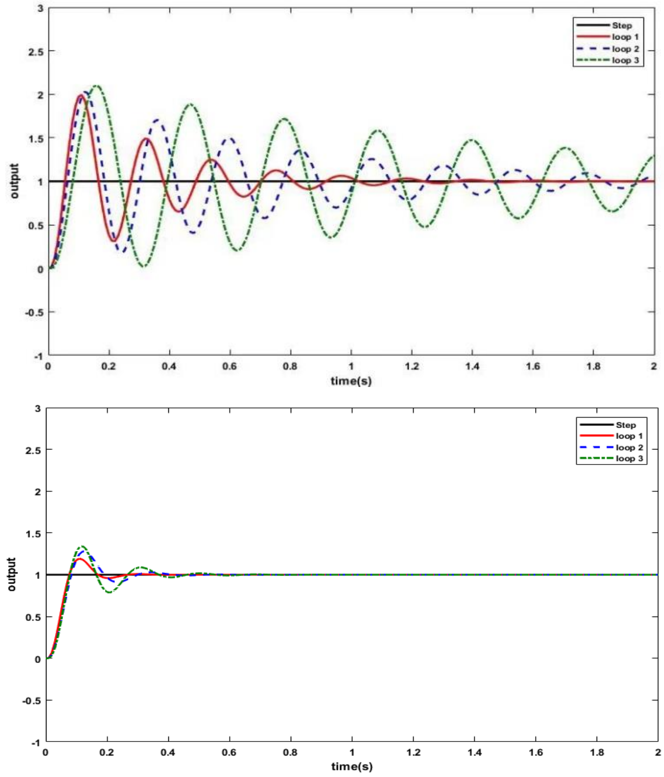

Fig. 14. Output when execution time and cycle change dynamically (top: EDF; bottom: improved EDF).

From the above dynamic scheduling results, it can be seen that in the data transmission process of multi task NCS, in order to compete for the transmission priority, each task competes for the channel resources on the network. The dynamic change of the attributes of the transmitted tasks makes it difficult to find an effective transmission order in the transmission, which leads to the chaos of the scheduling management in the system and makes the efficiency of information transmission unsatisfactory. The improved EDF scheduling strategy can accurately process the task attributes and make each task transmit data according to the set rules and reasonable time. The improved EDF can effectively allocate the bandwidth of the system, manage the execution of each task, and carry out the data transmission of the system efficiently and orderly. The stability of the system is effectively guaranteed.

3.6 Performance indicators comparison

From the comparison results of the above curves, it can be seen that the improved EDF scheduling strategy designed in this paper is effective. The comparison of performance indicators is given here to further illustrate the advancement of the proposed scheduling strategy. In this paper, the maximum overshoot, settling time, integral absolute error (IAE) and integral square error (ISE) are used as performance indicators. Let h_i is sampling period, the definition of IAE can be expressed as Eq. (8). The definition of ISE can be expressed as Eq. (9).

$$IAE_i = \int_0^\infty |e(t)|\,dt \quad (8)$$

$$ISE_i = \int_0^\infty |e(t)|^2\,dt \quad (9)$$

For the above simulation schemes and corresponding different parameters, the comparison of various performance indicators is shown in Table 1. It should be noted that the values of these indicators are the mean value of the indicators of the three control loops. '/' represents that the system is unstable and accurate values cannot be obtained.

Table 1. The comparison of various performance indicators.

Simulation parameters	Scheduling strategy	Maximum overshoot (%)	Settling time (s)	IAE	ISE
Interference rate is 0, packet loss rate is 0	EDF	69.32	0.63	0.0222	0.0086
	Improved EDF	51.25	0.43	0.0142	0.0032
Interference rate is 0.2, packet loss rate is 0	EDF	80.67	1.36	0.0385	0.0138
	Improved EDF	71.24	0.62	0.0189	0.0045
Interference rate is 0.3, packet loss rate is 0	EDF	88.42	1.64	0.0572	0.0209
	Improved EDF	73.31	1.26	0.0211	0.0053
Interference rate is 0.4, packet loss rate is 0	EDF	/	/	0.1057	0.0391
	Improved EDF	75.15	1.44	0.0272	0.0065
Interference rate is 0, packet loss rate is 0.1	EDF	72.67	0.87	0.0327	0.0118
	Improved EDF	49.33	0.48	0.0192	0.0046
Interference rate is 0, packet loss rate is 0.15	EDF	70.33	1.81	0.0396	0.0154
	Improved EDF	52.01	0.78	0.0217	0.0049
Interference rate is 0, packet loss rate is 0.2	EDF	/	/	0.0437	0.0171
	Improved EDF	64.08	1.62	0.0259	0.0059
Interference rate is 0.3, packet loss rate is 0.15	EDF	/	/	0.0607	0.0206
	Improved EDF	101.33	1.83	0.0316	0.0068
Execution time and cycle change dynamically	EDF	103.37	/	0.0616	0.0253
	Improved EDF	28.67	0.61	0.0246	0.0055

It can be seen from the results in Table 1 that the improved EDF scheduling strategy is superior to the EDF scheduling strategy in terms of maximum overshoot, settling time, IAE and ISE. Therefore, from the comparison of performance indicators, the improved EDF scheduling strategy designed in this paper is more effective and can suppress the problem of control degradation caused by interference and packet loss in NCS.

4. CONCLUSIONS

The focus of this paper is to improve the practicability of network transmission in NCS, enhance the transmission efficiency of the network and ensure the stability of the system. The traditional EDF scheduling strategy has clear attribute requirements for tasks in execution, such as an accurate execution time and cycle, which are often difficult to meet in reality. Further, due to a series of uncontrollable factors such as heavy tasks, special emergency tasks, delays in the process of sending and receiving information by sensors, the attributes of tasks in NCS may change dynamically, resulting in the difficulty of EDF control strategy to achieve the desired effect. At the same time, the standard EDF scheduling strategy cannot adapt to different tasks and environments, which makes the execution of the system more difficult to satisfy. In this paper, the standard EDF scheduling strategy is improved. The improved EDF scheduling strategy improves and optimizes the schedulable conditions and scheduling strategy by introducing the factors of packet loss and external interference, so as to accurately identify the cycle and execution time of the task. Simulation results on the TrueTime platform show that the improved EDF scheduling strategy can significantly improve the data transmission and scheduling of the system, and the adaptability to bad network transmission environment with packet loss and interference is also significantly improved.

Due to the complexity and variability of NCS, the proposed scheduling strategy still needs to be further optimized. When dealing with the uncertain time range, this paper restricts the interval fluctuation to a fixed value through the distribution function. Whether this value can accurately represent the characteristic information of the task itself needs to determine a standard to measure its universality in future research. On the other hand, because of the complexity of NCS, the simulation environment is not completely the same as the actual transmission environment, so the simulation will idealize some other problems, such as the actual control object may not be a fixed model, the data packets in the transmission process may be disordered, etc., which still need to be further considered in the future.

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