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Real-Time Control for CPS of Digital Airplane Assembly with Robust H-Infinity Theory

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Real-Time Control for CPS of Digital Airplane Assembly with Robust H-Infinity Theory

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Abstract: This study introduces a real-time controller design method under the effects of network time delay and external disturbance. The study first introduces the digital, virtual, intelligent trend of airplane assembly and reveals the status and problems of digital airplane assembly studies. The Cyber-Physical System (CPS) structure is then proposed for digital airplane assembly, and the real-time control issues are discussed. Then, the question of real-time control undertaken by a parallel robot is simplified to a control question with bounded time delay and complex interference, and a mathematical description is presented. Next, a robust H∞ controller with a disturbance degree of decay γ is designed according to the mathematical description. Finally, a simulation is conducted. All of the experiment results show the feasibility of the above proposed methods.

Key words: cyber physical system; network time delay; robust H-infinity control; linear matrix inequality

1 Introduction

Airplane assembly is based on the size coordination principle. The airplane parts or components are combined and connected to a higher level component or to a complete machine in accordance with the design and manufacturing requirements[1, 2]. Due to the large size, complicated structure, and coordination, labor of assembling the airplane accounts for about half of the labor of manufacturing the airplane. Therefore, airplane assembly is a comprehensive integration technology with large technical difficulties and involves the knowledge of many fields of science[3-5]. The economy, safety, efficiency, comfort, and durability of modern airplanes require numerous changes in the airplane assembly process. Traditional assembly technologies are unable to meet current needs, regardless of cost or production cycle. Innovations in Information Technology (IT) have driven airplane assembly toward digitization, virtualization, and intelligence. The application of digital assembly technology enables problems that can be found only in the implementation to be exposed prior. Therefore, such problems can be corrected in advance to avoid losses in time, labor, and cost.

With the implementation of digital technology in airplane assembly, many researchers have proposed digital pre-assembly by using a computer such that full simulation of the assembly process is artificially completed, but it’s difficult to transform the simulation results into data that can be used by a Numerical Control (NC) device. However, human operation of the actual object is ultimately required. Without information relays among the mounting units, mutual sense, and autonomy, inaccurate information and integration difficulties are likely to occur. The authors of this study have considered a process in which airplane assembly is conducted automatically by combining a series of operations according to the mission requirements. Such a task can be performed by using a Cyber-Physical System (CPS), which is a large and complex system that focuses on the integration of physical units and information units. CPS achieves efficient, dynamic
organization and the coordinated allocation of resources by requiring that physical elements have information processing and communication capabilities. Essentially, CPS is a large, self-learning, self-adaptive, dynamically self-governed, and self-coordinated system. Therefore, we propose the use of CPS for digital airplane assembly, which combines technologies such as sensing, communication, control, and simulation to complete the assembly process. Because data transmission in CPS is based on a network, the problem of real-time motion control should consider the network time delay influence. The focus of this study is motion control under the conditions of varying bounded time delay and complex interference by using CPS for digital assembly.

A variety of networks are used in CPS for data exchange. However, network transmission time delay, packet loss, and other problems pose significant challenges to the stability of traditional control systems. In recent years, researches have focused on the improvement of time delay compensation and controllers. In terms of time delay compensation, such studies focus mainly on identification, measurement, compensation methods, and jitter suppression of the time delay parameters to derive a time delay model by designing a compensation method or adding a data buffer to ensure data consistency. The time delay can be measured by a timestamp. That is, by adding a time value in the message during its transmission, the time delay can be calculated by determining the difference between transmitted and received time. Numerous controller improvement methods have been proposed. Xu et al. proposed a stochastic optimal control method to address random time delay. They adopted an Adaptive Estimate (AE) and the Q-learning method to handle problems in time-varying systems and used Lyapunov stability theory to determine whether the method is optimal. To address time delay in real-time systems, Nilsson et al. suggested using sampling settings of the time driver and the controller and actuator of the event driver. Although previous studies have discussed using neural network methods to reduce the time delay effect on control performance; the learning period of neural network needs to be improved. Zhang et al. designed an adaptive neural network controller by using the inversion method for strict-feedback nonlinear systems. Khoshnood and Moradi proposed a model reference adaptive control method based on the robust theory. Previous research has proposed the use of genetic algorithms to set traditional Proportional-Integral-Derivative (PID) parameters to deal with network control systems with random time delay and packet loss problems. Li et al. discussed the disorder problem of network control packets. Based on the Markov jump theory and Linear Matrix Inequality (LMI), they proposed the controller design method. Some previous studies have proposed fractional order fuzzy PID controllers, and others have proposed optimal fuzzy controllers. Obviously, the introduction of a motion control network brings new challenges. The controller design method is very diverse and includes both advantages and disadvantages.

In summary, this paper is divided into six parts: Section 1 introduces the significance of CPS in digital airplane assembly and examines real-time motion control in the cases of time delay and interference. Section 2 presents a CPS structure for digital airplane assembly. Section 3 gives a mathematical description for the single leg of the parallel robot in the conditions of time delay and interference. Section 4 discusses the robust H-infinity controller design for the parallel robot uniaxial motion control. Section 5 discusses the simulation and analysis to verify the validity of the controller, and Section 6 gives the conclusion of this paper.

2 CPS of Digital Airplane Assembly

2.1 System structure

To resolve problems existing in digital airplane assembly, the cyber-physical fusion method is proposed. Based on Computation, Communication, and Control (3C) integration, the cyber-physical fusion method can realize interaction and feedback between the information system and the physical system and can then exploit the advantages of IT in communication, data storage, data analysis, and control optimization. The structure of CPS for digital airplane assembly is shown in Fig. 1.

The sense and control layer is composed of many physical units that can communicate with other units through a network. Sense units perceive certain physical properties of focused physical equipment or facilities such as the placement of a positioning fixture, and the stated parameters of work piece size, stress, transformation, and temperature. The units can perform certain operations according to the received sense
command or control instruction. For example, a measuring device can launch a processing plan or a controlled device can measure a physical property, and the raw data is then transmitted through the communication layer to the decision-making layer.

The communication layer incorporates various networks established on the basis of actual demands such as wired broadband, WiFi, ZigBee, 3G/4G, and several communication base stations and network nodes in addition to databases and information-processing servers. This layer is also responsible for data storage and transmission.

The decision-making layer, which connects the terminal users and the system, consists of two parts: the sensory control front and the simulation control center. The simulation control center is used mainly for pre-assembled aircraft simulation and verification. By setting the corresponding models of actual physical objects in the simulation environment, the assembly information is given, and the design plan then drives the model to complete the entire simulation process to detect and resolve problems in the assembly, thus generating a validated assembly program. Moreover, by using the communication interface to translate the program into a control command of the controlled object, the assembly operation can be completed. Real-time monitoring of the object’s state in the physical environment and timely feedback to the information system can then be accomplished to perfect the assembly solutions. Online simulation control combining off-line pre-assembly and cyber-physical integration further ensures the smooth progress of the assembly. Although there is no visualized model display or on-line program design and modification capabilities, the sensory control front allows human and physical system interaction with no virtual assembly support environment and essentially achieves monitoring of the assembly process and sensing and control rules.

### 2.2 Application background

Next, we apply the system for joining large parts of an aircraft in a heterogeneous distribution environment. Digital measuring devices such as laser trackers are used to measure the position data of the large parts, and a parallel robot is used as a driving device (Fig. 2). The measurement and control data are transmitted throughout the network.

This study focuses on motion control undertaken by a parallel robot, which is achieved by parallel-coupled multi-axis robot coupling. Therefore, the control issue of the parallel robot can be simplified as a real-time motion control problem in the case of time delay and interference. In the following section, research details for real-time motion control of the parallel robot are given.

### 3 Motion Control Problem Description of the Parallel Robot

Figure 3 shows a schematic structural diagram of the control system herein. The time delay from the controller to the actuator is $\tau_1(t)$, and the time delay from the sensor to the controller is $\tau_2(t)$.

The parallel robot is a typical multi-axis system. In this study, the Single Input Single Output (SISO) control method was used. In the process of uniaxial
control, we can consider the coupling effect between the legs of the parallel robot as interference, thus indirectly guaranteeing overall accuracy of the position by maintaining position tracking accuracy of each axis. Although some control methods are introduced in Section 1, the present study required a method with simple calculation, good real-time effects, and good stability. Therefore, feedback control was used as a single-axis controller. The single axis control after the introduction of time delay of the network can be expressed as that shown in Fig. 4.

In this case, $\tau_1(t)$ and $\tau_2(t)$ are not necessarily equal. They may be constant or varying functions and may even be random numbers. The parameter $x$ represents the system state; $u$ represents the control input; $y$ represents the output of the system; and $d$ is the compound interference. Thus, we can get $u(t) = G_p(s)[x_r(t) - x(t - \tau_2(t))]$. The state space expression of Fig. 4 is shown by Eq. (1), in which $A$, $B_1$, $B_2$, and $C$ are the corresponding constant matrices of appropriate dimensions.

$$
\begin{align*}
\dot{x}(t) &= Ax(t) + B_1u(t - \tau_1(t)) + B_2d(t), \\
y(t) &= Cx(t)
\end{align*}
$$

(1)

The system in this study can be used with wired or wireless networks. The network time delay can be measured by using the timestamp method. Considering the actual situation in which all assembly elements are in the same condition and each network is relatively stable, the time delay cannot be infinite. We discuss only the data in order. Therefore, the network time delay in this research must meet the following conditions:

1. The network time delay exists but must be bounded; that is, $\tau_1^*$ and $\tau_2^*$ make $0 < \tau_1(t) \leq \tau_1^*$ and $0 < \tau_2(t) \leq \tau_2^*$ true.
2. Data transmission under the circumstances of time delay still meets the principle of the early incoming data processed first and the late arriving data processed last, which meets the requirement of Fig. 5.
3. Although the delay of different legs could be different, the value still satisfies condition 1.
4. No packet loss is considered.

4 Design of Robust H-Infinity Controller

4.1 Pre-knowledge

Definition 1[23] Consider the following forms of the SISO linear system:

$$
\left\{ \begin{array}{l}
\dot{x}(t) = Ax(t) + Bu(t), \\
y(t) = Cx(t)
\end{array} \right.
$$

where $A$, $B$, and $C$ are corresponding constant matrices with the appropriate dimensions. That the system $H_\infty$ is solvable means the following:

1. The matrix $A$ is stable.
2. $\|G(s)\|_\infty < \gamma$, $G(s) = C[(sI - A)^{-1}B$ represents the function transferred from $u$ to $y$. $\gamma$ is the disturbance degree of decay.

Lemma 1[23] (Schur complement lemma). If the following matrix inequality is satisfied

$$
S_{11} + S_{12}^T S_{21} S_{22}^{-1} S_{12}^T > 0,
$$

and $S_{11}$ and $S_{22}$ are symmetric matrices, the following conclusions are also satisfied:

1. $S_{11} < 0, S_{22} - S_{12}^T S_{11}^{-1} S_{12} < 0$;
2. $S_{22} < 0, S_{11} - S_{12}^T S_{22}^{-1} S_{12} < 0$.

Lemma 2[23] For arbitrary matrices of appropriate dimensions, $X$ and $Y$, $\forall U > 0$, the inequalities

$$
X^T Y + Y^T X \preceq X^T U X + Y^T U^{-1} Y
$$

are true.

4.2 Robust H-infinity controller

As shown in Fig. 4, the main task of the single axis is to design $G_p(s)$; then, the problem discussed in this

$$
\text{Fig. 5 Schematic diagram of time delay.}
$$
section can be transformed as follows. For a given disturbance degree of decay constant $\gamma > 0$, we can find a state feedback control rate to make the robust system stable. Since there is the presence of time delay $\tau_2$ in the feedback loop and $x_i(t)$ is set 0, the controller-involved feedback loop time delay in the design is $u(t) = -Kx(t - \tau_2)$.

Substituting it to Eq. (1) and to making $\tau_0(t) = \tau_1(t) + \tau_2(t)$, we get

$$\dot{x}(t) = Ax(t) - B_1Kx(t - \tau_0(t)) + B_2d(t)$$  \hspace{1cm} (2)

which indicates that the robust is asymptotically stable, and performance index of $H_\infty$ is less than the given bound $\gamma$.

Make $x(t - \tau) = x(t) - \int_{t-\tau}^{t} \psi(\vartheta)d\vartheta$, and $\psi(\vartheta) = Ax(\vartheta) - B_1Kx(\vartheta - \tau_0(\vartheta)) + B_2d(\vartheta)$, then Eq. (2) could be transformed into

$$\dot{x}(t) = (A - B_1K)x(t) + B_2d(t) + B_1K \int_{t-\tau(t)}^{t} \psi(\vartheta)d\vartheta$$  \hspace{1cm} (3)

If we want the robust system to be stable in Eq. (1), we can get the following theorems.

**Theorem 1** For the time delay system in Eq. (1), if there is a matrix $K$ and the positive definite symmetric matrices $P, Q$, and $R > 0$, the following matrix inequality holds:

$$\begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} < 0$$  \hspace{1cm} (4)

$$M_{11} = (A - B_1K)^T P + P(A - B_1K) + Q + PB_1KRK^T B_1^TP + \tau_0^* A^TR_1A,$$

$$M_{12} = -\tau_0^* A^TR_1B_1K,$$

$$M_{13} = PB_2 + \tau_0^* A^TR_1B_2,$$

$$M_{21} = -\tau_0^* K^T B_1^TR_1B_2,$$

$$M_{22} = \tau_0^* K^T B_1^TR_1B_1K - Q,$$

$$M_{23} = -\tau_0^* K^T B_1^TR_1B_2,$$

$$M_{31} = B_2^TP + \tau_0^* B_2^TR_1A,$$

$$M_{32} = -\tau_0^* B_2^TR_1B_1K,$$

$$M_{33} = \tau_0^* B_2^TR_1B_2.$$

then the robust of the time delay system in Eq. (1) is stable.

**Proof** Make the Lyapunov function as

$$V(x(t), t) = x^T(t)P x(t) + \int_{t-\tau_0(t)}^{t} x^T(\vartheta)Q_2 x(\vartheta)d\vartheta + \int_{-\tau_0(t)}^{0} d\vartheta \int_{t+\vartheta}^{t} \psi^T(\vartheta)R^{-1}\psi(\vartheta)d\vartheta$$  \hspace{1cm} (5)

Solving the derivative of $V(x(t), t)$ and substituting Eq. (3) and the expression of $\psi(\vartheta)$, $\tau_0(t) = \tau_1(t) + \tau_2(t) < \tau_1^* + \tau_2^* = \tau_0^*$ and $R$ is a positive definite matrix, we can get

$$\dot{V}(x(t), t) = x^T(t)P x(t) + x^T(t)Q x(t) + \tau_0(t) \psi^T(t)R^{-1} \psi(t) - x^T(t - \tau_0(t))Q x(t - \tau_0(t)) - \int_{t-\tau_0(t)}^{t} \psi^T(\vartheta)R^{-1}\psi(\vartheta)d\vartheta \leq$$

$$x^T(t)[(A - B_1K)^T P + P(A - B_1K)]x(t) + x^T(t)PB_2d(t) + d^T(t)B_2^TP x(t) + x^T(t)Q x(t) - x^T(t - \tau_0(t))Q x(t - \tau_0(t)) + \tau_0^*[Ax(t) - B_1Kx(t - \tau_0(t)) + B_2d(t)]^T,$$

$$R^{-1}[Ax(t) + B_2d(t) - B_1Kx(t - \tau_0(t))] + x^T(t)PB_1K \int_{t-\tau_0(t)}^{t} \psi(\vartheta)d\vartheta + (B_1K \int_{t-\tau_0(t)}^{t} \psi(\vartheta)d\vartheta)^T P x(t) - \int_{t-\tau_0(t)}^{t} \psi(\vartheta)R^{-1}\psi(\vartheta)d\vartheta.$$  \hspace{1cm} (6)

According to Lemma 2 and the positive definite symmetric matrix, we have

$$x^T(t)PB_1K \int_{t-\tau_0(t)}^{t} \psi(\vartheta)d\vartheta + (B_1K \int_{t-\tau_0(t)}^{t} \psi(\vartheta)d\vartheta)^T P x(t) =$$

$$[K^T B_1^TP x(t)]^T \int_{t-\tau_0(t)}^{t} \psi(\vartheta)d\vartheta + \int_{t-\tau_0(t)}^{t} \psi(\vartheta)d\vartheta]^T [K^T B_1^TP x(t)] \leq$$

$$[K^T B_1^TP x(t)]^T R[K^T B_1^TP x(t)] + \int_{t-\tau_0(t)}^{t} \psi(\vartheta)R^{-1}\psi(\vartheta)d\vartheta.$$  \hspace{1cm} (7)

After simplifying $\dot{V}(x(t), t)$ and making $\bar{x}(t) = [x^T(t) - x^T(t - \tau_0(t)) d^T(t)]^T$, we have $\dot{V}(x(t), t) \leq \bar{x}(t)^T M \bar{x}(t)$, and the value of matrix $M$ can be shown in Theorem 1. As shown in the above derivation, when the inequality in Theorem 1 is satisfied, $\dot{V}(x(t), t) < 0$, which proves that the robust of the time delay system in Eq. (1) is stable.  \hspace{1cm} □

To examine the $H_\infty$ property in the system of Eq. (1), we make the original value 0. Then, if $T > 0$,

$$J_T = \int_{0}^{T} (\gamma^2 d^T d) dt \leq$$
inequality, the equation is transformed as
\[
\begin{align*}
\int_0^T (y^T y - y^2 d^T d) dt + V(x(T), T) &= \int_0^T (y^T y - y^2 d^T d + V(x(t), t)) dt \\
&\leq \int_0^T (y^T y - y^2 d^T d + \bar{x}^T(t) M \bar{x}(t)) dt
\end{align*}
\]
is satisfied, and the stability of the system and the property of $H_{\infty}$ can be ensured. Substituting $y(t) = C x(t)$, we get
\[
y^T y - y^2 d^T d + \bar{x}^T(t) M \bar{x}(t) = x^T(t) C^T C x(t) - y^2 d^T d(t) + \bar{x}^T(t) M \bar{x}(t) = \bar{x}^T(t) \bar{M} \bar{x}(t)
\]
In this equation, $\bar{M} = M + \text{diag}(C^T C, 0, 0, -y^2 I)$. Thus, when $\bar{M} < 0$, we know that $J_T < 0$, and the reliability of Theorem 1 is proved. At the same time, the performance index of $H_{\infty}$ in the system is less than the given bound $\gamma$.

To solve $\bar{M} < 0$, we can get the following theorem.

**Theorem 2** For the time delay system in Eq. (1), if there is a matrix $W$, positive definite symmetric matrix $P, Q, R > 0$, and constant $\gamma > 0$, then the following matrix inequality holds
\[
R \leq P^{-1},
\]
\[
\begin{bmatrix}
M_{11} & 0 & B_2 & -\tau_0^* V A^T & B_1 W & V C^T \\
* & -\bar{Q} & 0 & \tau_0^* W^T B_1^T & 0 & 0 \\
* & * & -y^2 I & -\tau_0^* B_2^T & 0 & 0 \\
* & * & * & -\tau_0^* R & 0 & 0 \\
* & * & * & * & -V & 0 \\
* & * & * & * & * & -I
\end{bmatrix} < 0
\]
(6)
where $M_{11} = VA^T + AV - W^T B_1^T - B_1 W + \bar{Q}$. Then, the robust of the time delay system in Eq. (1) is stable, and the performance index of $H_{\infty}$ in the system is less than the given bound $\gamma$. Then, the gain matrix of the feedback controller can be $K = WP$.

**Proof** According to the Schur complement lemma, we know that $M < 0$ is equivalent to
\[
\begin{bmatrix}
M_{11} & 0 & PB_2 & -\tau_0^* A^T & PB_1 K \\
* & -\bar{Q} & 0 & \tau_0^* K T B_1^T & 0 \\
* & * & -y^2 I & -\tau_0^* B_2^T & 0 \\
* & * & * & -\tau_0^* R & 0 \\
* & * & * & * & -R^{-1}
\end{bmatrix} < 0,
\]
where $M_{11} = (A - B_1 K)^T P + P(A - B_1 K) + Q + C^T C$. In the equation, $*$ represents that the matrix is symmetric. By making $V = P^{-1}, W = KV, \bar{Q} = VQV$, and multiplying at the same time the diagonal matrix diag($V, V, I, I, V$) at both ends of the above inequality, the equation is transformed as
\[
-R^{-1} \leq -P,
\]
\[
\begin{bmatrix}
M_{11} & 0 & B_2 & -\tau_0^* V A^T & B_1 W \\
* & -\bar{Q} & 0 & \tau_0^* W^T B_1^T & 0 \\
* & * & -y^2 I & -\tau_0^* B_2^T & 0 \\
* & * & * & -\tau_0^* R & 0 \\
* & * & * & * & -V
\end{bmatrix} < 0
\]
(7)
where $M_{11} = VA^T + AV - W^T B_1^T - B_1 W + \bar{Q} + V C^T C V$.

Again, the Schur compliment lemma transforms the above inequality to Formula (6). After solving the above inequality, we get $W$ and then $K = WP$.

Therefore, for the time delay system with bounded time delay, we can use the method described in Theorem 2 to solve Formula (6) and get a state feedback controller. This method can ensure that the robust of this system is stable and that the performance index of $H_{\infty}$ in the system is less than the given bound $\gamma$.

**5 Simulation and Analysis**

The state space expression of each single-axis servo drive system is shown in Eq. (1), and the concrete expression of the state space is shown in Formula (6). To verify the control performance of robust $H_{\infty}$ with bounded and variable time delay and interference, we adopt MATLAB to write the control model for simulation analysis.

\[
\begin{align*}
\dot{x}(t) &= \begin{bmatrix} 0 & 1 \\
0 & -\frac{\tau_0}{M_n} \end{bmatrix} x(t) + \begin{bmatrix} 0 \\
\frac{1}{M_n} \end{bmatrix} u(t - r_1(t)) + \\
&\begin{bmatrix} 0 \\
\frac{1}{M_n} \end{bmatrix} d(t)
\end{align*}
\]
\[
y(t) = \begin{bmatrix} 1 \\
0 \end{bmatrix} x(t)
\]
(8)

We set the bidirectional time delay bound as $\tau_1^* = 1, \tau_0^* = 2$. The set value $x_i$ is step function, and the complex disturbance value is $d = 0.1 \sin(t)$ or $d = \text{random}(0, 0.1)$. We conducted the experiments under four circumstances: (1) When the two-way time delay is fixed, the value is 1, and the sinusoidal interference is used. (2) When the two-way time delay is variable and bounded, the time delay variable value is $0.5 \sin(t) + 0.5$, and the sinusoidal interference is used. (3) When the two-way time delay is fixed, the value is 1, and the random interference is used. (4) When the two-way time delay is variable and bounded, the time delay variable value is $0.5 \sin(t) + 0.5$, and the random
interference is used. These two-type interferences are used as examples; similar results can be obtained with other interferences. The simulation model is shown in Fig. 6.

Setting the simulation time as 100 s, we calculate $K = [0.1967 \ 0.4380]$ according to Formula (6) for the two circumstances. The systematic output response and corresponding error are shown in Figs. 7–14.

As shown by the simulation results, Figs. 7–10 and Figs. 11–14 respectively show the output closed-loop system under the effects of fixed time delay and bounded time delay. As shown in Figs. 7–10, when a two-way fixed time delay is present in a single-axis closed-loop system, the system output is in a vibrating divergent state, which prevents the final output from being converged. After using the controller designed in this study, although there is also vibration, the controller can recover to a stable position after some time, and the tracking error can converge to zero. After adding sinusoidal or random interference, the system errors can fluctuate within a small range and are also well suppressed. Figures 11–14 show the simulation results when the time delay changes as a random or a sine function. The actual position of the output is in a vibration state; however, a convergence trend...
without interference is present, as is the controller designed in this study. By using a robust controller and adding interference, the controller can converge to a given value relatively quickly, and the tracking error can converge to zero faster. In short, the robust $H_\infty$ controller proposed in this study has good noise immunity and stability, which can effectively reduce the impact of bounded time delay and disturbance to single-axis location tracking.

6 Conclusions

Based on the development trend of digital airplane assembly and the concept of digitization, virtualization, and intelligence, we discuss the existing problems in airplane assembly and propose the cyber-physical theory of CPS for digital airplane assembly. Then, we perform an in-depth study of real-time control in CPS. The question of real-time control undertaken by a parallel robot is simplified to a control question with bounded time delay and complex interference, and a mathematical description is given. Next, a decentralized control method of parallel robot in the case of network time delay is proposed, and a robust $H_\infty$ controller is designed. The method ensures robustness, which is proved on the basis of the Lyapunov function. For the interference problem, we introduce a disturbance degree of decay $\gamma$ and give the corresponding theorems and proofs. Finally, these two theorems are used for simulation with the SIMULINK design control system and the LMI toolbox to calculate robust $H_\infty$ controller parameters. By tracking the performance analysis under the conditions of fixed time delay and bounded time delay, it is verified that the proposed $H_\infty$ robust controller design method can ensure system stability and can effectively inhibit complex interference.

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