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Research on Iterative Learning Control System

Fengling Yin and Bingquan Huo

Binzhou Polytechnic, Shandong, China
yinfengling11@126.com

Abstract

With the rapid and bursting development of computer and control science, research on iterative learning control system is a hot topic. Random delays of control and measurement signals during transmission over wireless network seriously affect the convergence performance of iterative learning control (ILC) systems. System based on step random delay model, the transfer matrix is derived, which contains random delay impact factor. For different cases of random delay, characteristic value and other elements of the shifting of the lower triangular matrix are analyzed respectively determine the rate of convergence and strong convergence. Analysis shows that the convergence speed is reduced, robust convergence have also been affected. Especially, the impact of control signal delays on robust convergence is greater than that of measurement signal delays. Simulation results are provided to demonstrate correctness of the conclusion. Finally, some potential improvement of proposed method is pointed out.

Keywords: *Wireless Remote Control, System Control, Random Delay*

1. Introduction

In recent years, the research of wireless network control system has been widely attention of researchers [1-4]. These systems through the corresponding wireless networks constitute a closed control loop, the sensor measurement signals through wireless network transmission to the controller, the controller of the control signal is through the wireless network transmission to the actuator. Due to the introduction of wireless network, the control system is not only easy to wiring, low power consumption, less cost, and realize the separation of the controller and system platform, greatly expand the application range of the system. And using wire transmission signal, compared to the traditional control system of the introduction of wireless network although brought a lot of advantage to the control system, but also make the system controller design and analysis of more complex, one of the main factors is signal via wireless network transmission is affected by the random time delay in the process. Especially for the controller USES the iterative learning control (iterative learning control, the ILC) [5] of wireless network control system, the controller and actuators respectively through the wireless network receives the measurement signal and control signal, the signal in the process of wireless transmission by random delay will interfere with the process of iterative learning controller, the system transfer matrix elements within the value change, thus affecting the convergence performance of the system. Therefore, proven random time delay for measurement and control signal to the ILC convergence performance of the system has important significance.

At present, about the impact of time delay on the ILC system performance analysis and the processing method has made some progress[6-11].Aiming at the effects of the system state time delay, according to a given performance index, literature [6] proposed a robust ILC method. Time delay based on the measurement by literature [7] presented an average ILC method. Literature [8]state time delay is analyzed for a class of nonlinear higher order ILC system, the influence of and points out that state time delay is not very

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significant influence on the stability of the system .Literature [9] thinks the measuring signal time delay estimation deviation will cause the control signal of divergence, and out of a mechanism to eliminate the influence of time delay measurement signal. Literature [10] for a class of nonlinear output feedback delay system, this paper puts forward an adaptive ILC design method. In view of the influence of time delay control signal is subjected to a class of nonlinear ILC systems; literature [11] presented a time delay compensation method, but this method is based on measuring the signal delay can be measured and the control signal delay based on a fixed constant. Considering above research or the state signal delay, measuring signal delay and control signal delay on control performance of the system, or only considers the amount of delay for constant conditions affect the performance of system control. Therefore, the analysis of the existing results and processing method is not applicable to ILC system affected by the random time delay measurement and control signals. To find out the measurement and control signal of random time delay to the ILC convergence performance of the system, this paper for a class of linear discrete time invariant of the controlled system, according to the random delay model contains random time delay by impact factor of system transfer matrix, and study the change of the element value, so as to realize measurement and control signal of random time delay of the ILC system analysis of the influence of the convergence performance.

2. The Description of the Problem

Consider a class of discrete time invariant linear control system:

$$x_k(t+1) = Ax_k(t) + Bu_k(t)$$
$$y_k(t) = Cx_k(t)$$

(1)

In the equation 1, $x_k(t)$, $u_k(t)$, $y_k(t)$ denote the system current status, controlled input and output, respectively. A , B , C represent the coefficient matrix of the system. $k = 0,1,2,.....$ denotes the number of iterations. $t \in [0,T]$ represents the discrete time. Control goal is to achieve the desired trajectory $y_d(t)$ the precise tracking. For each achievable $y_d(t)$ there are corresponding to the expectation of a known control input $u_d(t)$. Moreover, $y_d(t)$ and $u_d(t)$ obey the following standard:

$$x_d(t+1) = Ax_d(t) + Bu_d(t)$$
$$y_d(t) = Cx_d(t)$$

(2)

In the equation 2, $x_d(t)$ denotes the desired state of the system. In order to achieve the desired trajectory tracking precision, scholars have proposed a variety of different ways of ILC, one of the p-type ILC method discussed in [5] is:

$$u_{k+1}(t) = u_k(t) + \Gamma(t)e_k(t+1)$$

(3)

In the formula, $\Gamma(t)$ represents the learning gain, $e_k(t) = y_d(t) - y_k(t)$ denotes the output error, $t \in [0,T-1]$. However, the use of wireless network transmission ILC system of measuring signals and control signals, the measurement and control signals inevitably under the influence of random time delay, as shown in figure 1 [12-13]. Based on the quantity of different time delay, the random time delay can be divided into step random time delay and multiple random time delay, etc., and multi-step random time delay can be based on the analysis of the influence of random time delay effect is derived on the basis of the step. Therefore, this article will step in random delay model on the basis of the analysis of the effect of measurement and control signal of random time delay of the ILC system.

Inspired by the literature [14,15] , transmits signals over a wireless network when the disturbance by the step of random time delay is expressed as:

$$y(t)=\xi(t)z(t)+(1-\xi(t))z(t-1)$$
(4)

$y(t)$ represents the received signal, $z(t)$ is the signal for launch. Bernoulli distributed parameters $\xi(t)$, namely randomly take 0 or 1. In this model, if $\xi(t)=1, y(t)=z(t)$, there will be no delay to happen. Or otherwise, $y(t)=z(t-1)$ said step of random time delay happened. Based on this model, the control signal is affected by the step of random time delay of ILC system available through formula (5) and (6):

$$x_k(t+1)=Ax_k(t)+Bu_k(t)$$
$$y_k(t)=Cx_k(t)$$
(5)

$$u_{k+1}(t)=u_k(t)+\Gamma(t)\tilde{e}_k(t+1)$$
(6)

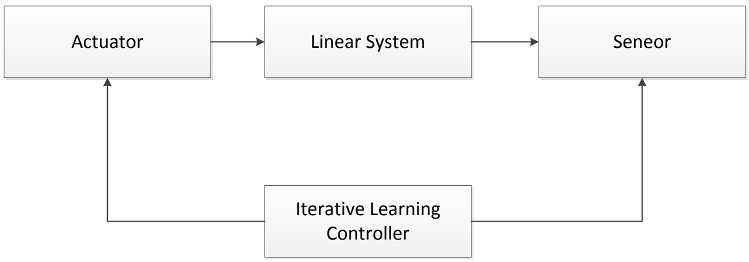


Figure 1. The Block Diagram of ILC Systems Based on Wireless Network

Accordingly, actuator end receives the control signal $u_k(t)$ and the controller receives the measuring signal $\tilde{e}_k(t+1)$ are:

$$u_k(t)=\xi_k(t)u_k(t)+|1-\xi_k(t)|u_k(t-1)$$
(7)

$$\tilde{e}_k(t+1)=\eta_k(t)e_k(t+1)+(1-\eta_k(t))e_k(t)$$
(8)

In the equations, $\tilde{e}_k(t+1)$ and $u_k(t)$, respectively, said the launch of the control signal controller and sensor and measuring signal. Step random time delay impact factor η_k and $\xi_k(t)$ are subject to the Bernoulli distribution and are independent of each other. Obviously, measurement and control signals by step in the process of wireless transmission of random time delay will affect the ILC system control performance, so it is necessary to analysis and control signal of random time delay to the ILC convergence performance of the system, as to provide theoretical basis for put forward the corresponding signal processing method.

3. The Measurement and Control Signal on the Impact of Random Time Delay on ILC

This section respectively control signals and measure the impact of random time delay of the ILC system analysis. For convenience of analysis, first make the following assumptions:

(1) $\|\Gamma(t)\| \le \beta_{\Gamma}, \|A\| \le \beta_A, \|B\| \le \beta_B, \|C\| \le \beta_c$

(2) $x_k(0) = x_d(0), \forall k$

(3) $\xi_k(0) = 1, \forall k$

Are ideal for measurement and control signal transmission of ILC system, in the case of without considering initial state error and output error norm $\|e_k(t+1)\|$ is about control error norm $\|\delta u_k(0)\|, \|\delta u_k(1)\|, \ldots \|\delta u_k(t)\|$ functions, such as formula 9.

$$\begin{bmatrix} \|e_k(1)\| \\ \vdots \\ \|e_k(T)\| \end{bmatrix} = \begin{bmatrix} \rho^{'}(0) & \ldots & 0 \\ \vdots & \ldots & \vdots \\ \rho^{'}(T-1) & \ldots & \rho^{'}(0) \end{bmatrix} \cdot \begin{bmatrix} \|\delta u_k(0)\| \\ \vdots \\ \|\delta u_k(T-1)\| \end{bmatrix}$$

(9)

In this formula, $\rho^{'}(t) = \beta c \beta_A^t \beta_B, t \in [0, T-1]$. The control error norm $\|\delta u_k(t)\|$ in the iteration domain has the following relationship:

$$\Psi_{k+1} \le H \Psi_k$$

(10)

$$\Psi_k = \left[\|\delta u_k(0)\|, \|\delta u_k(1)\|, \ldots, \delta u_k(T-1)\right]^T$$

(11)

$$H = \begin{bmatrix} \rho_0(0) & 0 & 0 & \cdots & 0 \\ \rho_1(1) & \rho_0(1) & \ddots & & \vdots \\ \rho_1(2) & \rho_1(1) & \rho_0(2) & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & 0 \\ \rho_1(T-1) & \cdots & \cdots & \rho_1(1) & \rho_0(T-1) \end{bmatrix}$$

(12)

In this formula, $\rho_0(t) = \|I - \Gamma(t) CB\|, \rho_1(t) = \beta_{\Gamma} \beta_C \beta_A^t \beta_B, t \in [0.T-1]$. Moreover, under the circumstances that $\rho_0(t) = \|I - \Gamma(t) CB\| < 1$, $\|\delta u_k(t)\|$ will converge to 0 with the increase of the number of iterations is monotonous, at the same time according to formula (9). $\|e_k(t)\|$ will also be monotonous converges to 0. However, measurement and control signal wireless transmission by random delay will interfere with the process of iterative learning controller, not only make the transfer matrix eigenvalue $\rho_0(t)$ change, affect the convergence rate of the ILC system, and make the transfer matrix of the triangle other elements within $\rho_1(t)$ values change, affect the system robust convergence.

For signal wireless transmission may occur in the process of random time delay, respectively to get below contains control signal, measuring signal of random time delay impact factor $\xi_k(t)$ and $\eta_k(t)$ of the transfer matrix of system $H_k^{'}$ and $H_k^{"}$ then respectively analyses the k iteration only control signal in the $u_k(t)$ or measuring signal $e_k(t+1)$ random time delay value transition matrix elements of the situation, and discuss the k iteration of multiple time signal changes of values of the transfer matrix of random time delay, so as to realize measurement and control signal random time delay to the ILC convergence speed and the robust convergence effect analysis.

3.1. The Random Time Delay Control Signal

According to the equation 2, 5, 7, we could conduct the status error and control error to be the following formulas:

$$\delta x_{kb}(t+1) = x_d(t+1) - x_k(t+1) = A\delta x_k(t) + B(\xi_k(t))\delta u_k(t) + (1-\xi_k(t))\delta u_k(t-1)$$
$$= \sum_{i=0}^{t-1} A^i B\xi_k(t-i)\delta u_k(t-i) + A^t B\delta u_k(0) + \sum_{j=0}^{t-1} A^i B(1-\xi_k(t-j)\delta u_k(t-1-j))$$

(13)

Only in the control signal generating random time delay case, will we conduct that $\tilde{e}_k(t+1) = e_k(t+1)$. According to equation (6) we can analyze and have control the error of $\delta u_{k+1}(t)$ to be:

$$\delta u_{k+1}(t) = u_d(t) - u_{k+1}(t) = u_d(t) - u_k(t) - \Gamma(t)e_k(t+1)$$
$$= \delta u_k(t) - \Gamma(t)C\delta x_k(t+1)$$

(14)

Through putting formula 14 into formula 13 we could derive:

$$\delta u_{k+1}(t) = (I - \Gamma(t)CB\xi_k(t))\delta u_k(t) - \Gamma(t)CA^t B\delta u_k(0) -$$
$$\sum_{i=1}^{t-1}\Gamma(t)CA^i B\cdot\xi_k(t-i) - \sum_{j=0}^{t-1}\Gamma(t)CA^j B\cdot(1-\xi_k(t-j)\delta u_k(t-1-j))$$

(15)

By calculating norm for both sides of formula 15, we can derive:

$$\|\delta u_{k+1}(t)\| \le \rho_0^{'}(k,t)\|\delta u_k(t)\| + \sum_{i=1}^{t}\rho_1^{'}(k,t,i)\|\delta u_k(t-i)\|$$

(16)

$$\rho_0^{'}(k,t) = \|I - \Gamma(t)CB\xi_k(t)\|, \mathrm{t}\in[0,\mathrm{T}-1]$$

(17)

$$\rho_1^{'}(k,t,i) = \beta_\Gamma\beta_C\beta_A^i\beta_B\zeta_k(t-i) + \beta_\Gamma\beta_C\beta_A^{i-1}\beta_B\cdot$$
$$(1-\xi_k(t+1-i)), t\in[1,T-1], i\in[1,t]$$

(18)

Presently, control error in the iteration domain transfer matrix is:

$$H_k^{'} = \begin{bmatrix} \rho_0^{'}(k,0) & 0 & \cdots & \cdots & 0 \\ \rho_1^{'}(k,1,1) & \rho_0^{'}(k,1) & \ddots & & \vdots \\ \rho_1^{'}(k,2,2) & \rho_1^{'}(k,2,1) & \rho_0^{'}(k,2) & \ddots & \vdots \\ \vdots & \vdots & \vdots & \vdots & 0 \\ \rho_1^{'}(k,\mathrm{T}-1,\mathrm{T}-1) & \cdots & \cdots & \rho_1^{'}(k,\mathrm{T}-1,1) & \rho_0^{'}(k,\mathrm{T}-1) \end{bmatrix}$$

(19)

Only when the controlling signal delay of $u_k(t)$ occur randomly and accordingly only a random delay impact factor $\varepsilon_k(t)=0$. According to the formula (17), the transfer matrix of $H_k^{'}$ corresponding eigenvalue is $H_k^{'}(t,t)=\rho_0^{'}(k,t)=1$. According to the formula (18), the transfer matrix $H_k^{'}$ within the triangle element will also change, which corresponds to the ψ_k in $\left\|\delta u_k(t)\right\|$ transition matrix elements of $H_k^{'}\left(t+\hat{t},t\right)=\rho_1^{'}\left(k,t+\hat{t},t\right)=0\left(1\le\hat{t}\le T-t-1\right)$. At this time the transfer matrix is:

$$H_k^{'}=\begin{bmatrix} \rho_0^{'}(k,0) & 0 & \cdots & \cdots & \cdots & \cdots & 0 \\ \rho_1^{'}(k,1,1) & \rho_0^{'}(k,0) & \ddots & & & & \vdots \\ \vdots & \vdots & \ddots & \ddots & & & \vdots \\ \rho_1^{'}(k,\mathrm{t},\mathrm{t}) & \vdots & \rho_1^{'}(k,\mathrm{t},1) & 1 & \ddots & & \vdots \\ \vdots & \vdots & \vdots & 0 & \ddots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & 0 \\ \rho_1^{'}(k,\mathrm{T}-1,\mathrm{T}-1) & \cdots & \cdots & 0 & \cdots & \rho_1^{'}(k,\mathrm{T}-1,1) & \rho_0^{'}(k,\mathrm{T}-1) \end{bmatrix}$$

(20)

According to above analysis, the control signal $u_k(t)$ of random time delay not only make the system transfer matrix eigenvalues of $H_k^{'}(t,t)$ value is 1, reduce the convergence rate of the $\left\|\delta u_{k+1}(t)\right\|$, will cause the system transfer matrix within the triangle element $H_k^{'}\left(t+\hat{t},t\right)$ value is 0, $\left\|\delta u_{k+1}(i)\right\|\left(t+1\le i\le T-1\right)$ affects the robust convergence. Obviously, the random time delay of control signal, the more value of 1 in transfer matrix eigenvalue and the more elements within the triangle under the value 0, to control the system error convergence speed and the more robust convergence effect clearly, because of the output error to control function, the output error convergence speed and the robust convergence effects are more obvious.

3.2. The Random Time Delay Signal Measurement

Control signal of random time delay in the process of transfer from the controller to the actuator, the measuring signal of random time delay is occurred in the process of transmission from the sensor to the controller. Therefore, measuring signal of random time delay effect the convergence performance of the system is different from the influence of random time delay control signal. The following is the effect on specific analysis: according to the formula (2) and (5) we can find out the relationship between state error $\delta x_k(t)$ and the control error $\delta u_k(t)$ as the following:

$$\delta x_k(t+1)=x_d(t+1)-x_k(t+1)=A\delta x_k(t)+B\delta u_k(t)$$
$$=\sum_{j=0}^{t}A^jB\delta u_k(t-j)$$

(21)

In only measurement signals under the condition of random time delay $u_k(t)=u_k(t)$. Formula 8 can be controlled according to the type error of $\delta u_k(t)$.

$$\delta u_{k+1}(t)=u_d(t)-u_{k+1}(t)=u_d(t)-u_k(t)-\Gamma(t)\eta_k(t+1)e_k(t+1)$$
$$-\Gamma(t)\left(1-\eta_k(t+1)\right)e_k(t)=\delta u_k(t)-\Gamma(t)\eta_k(t+1)C\delta x_k(t+1)$$
$$-\Gamma(t)\left(1-\eta_k(t+1)\right)C\delta x_k(t)$$

(22)

Combining formula 21 together with 22, we could derive the formula 23:

$$\delta u_{k+1}(t)=\left(1-\Gamma(t)\eta_k(t+1)CB\right)\delta u_k(t)-\sum_{i=1}^{t}\Gamma(t)\eta_k(t+1)CA^iB\delta u_k(t-i)$$
$$-\sum_{j=0}^{t-1}\Gamma(t)\left(1-\eta_k(t+1)\right)CA^jB\delta u_k\cdot(t-1-j)$$

(23)

Similarly to control error in the iteration $H_k^{"}$ for transfer matrix in the domain:

$$H_k^{"}=\begin{bmatrix}\rho_0^{"}(k,0) & 0 & \dots & \dots & 0\\ \rho_1^{"}(k,1,1) & \rho_0^{"}(k,1) & \ddots & & \vdots\\ \rho_1^{"}(k,2,2) & \rho_1^{"}(k,2,1) & \rho_0^{"}(k,2) & \ddots & \vdots\\ \vdots & \vdots & \vdots & \vdots & 0\\ \rho_1^{"}(k,\mathrm{T}-1,\mathrm{T}-1) & \dots & \dots & \rho_1^{"}(k,\mathrm{T}-1,1) & \rho_0^{"}(k,\mathrm{T}-1)\end{bmatrix}$$

(24)

According to above analysis, the measuring signal $e_k(t+1)$ random delay will not only make the system transfer matrix eigenvalues of $H_k^{"}(t,t)$ value is 1 reduce the convergence rate of $\left\|\delta u_{k+1}(t)\right\|$. And will make the transfer $H_k^{"}(t,\mathrm{i})$ triangle in the matrix elements value decreases β_A times, affect the $\left\|\delta u_{k+1}(t)\right\|$ robust convergence. Obviously, the more the random time delay measurement signal, to control error and output error convergence speed and the robust convergence effect of the more obvious.

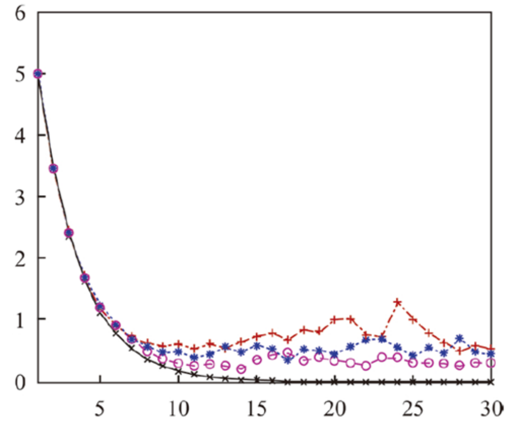
4. The Experimental Analysis

In this section, we take the following discrete time invariant linear controlled system into consideration:

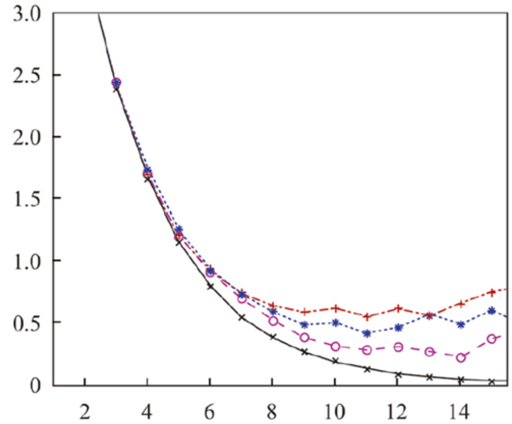
$$x_k(t+1)=\begin{bmatrix}-0.5 & 0 & 0\\ 1 & -1.24 & 0.87\\ 0 & 0.87 & 0\end{bmatrix}x_k(t)+\begin{bmatrix}1\\0\\0\end{bmatrix}u_k(t)$$
$$y_k(t)=\begin{bmatrix}2 & -2.6 & -2.8\end{bmatrix}x_k(t)$$

(25)

Control signal, measuring signal when the step of random time delay system robust convergence of maximum output error as shown in figure 2 and 3, respectively. The simulation results show that the control signal or signal measured under the condition of random time delay, the maximum output error in the system of the convergence speed and the robust convergence are affected by the signal of random time delay, and signal occurrence probability of random time delay, the greater the system the slower convergence, robust convergence affected. Comparing figure 2 and 3, the probability of the random time delay are 9% of the cases, the control signal is stochastic time delay system maximum output fluctuation is greater than the error of measuring signal of random time delay, show that random time delay control signal to the influence of system robust convergence is stronger than the influence of random time delay measurement signal.

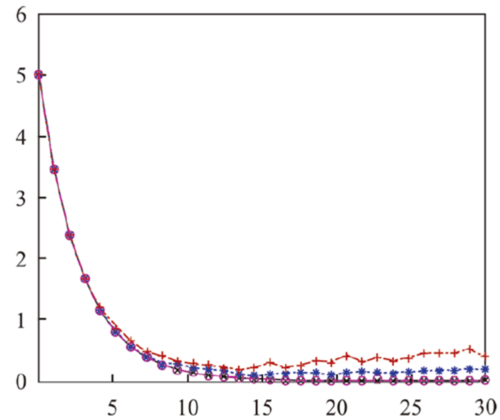


(a) Comparison of Maximum Tracking Errors

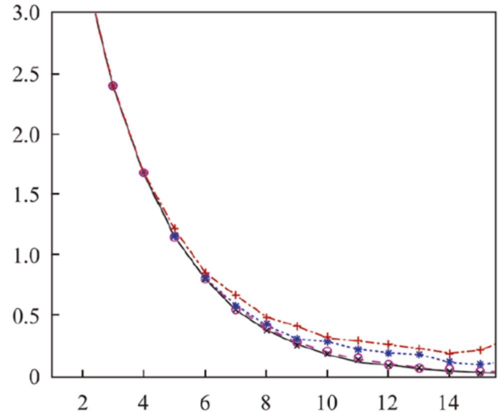


(b) Zoomed Prrofile

Figure 2. The Comparisons of Maximum Tracking Errors with Different Delay Probabilities in Control Signals



(a) Comparison of Maximum Tracking Errors



(b) Zoomed Prrofile

Figure 3. The Comparisons of Maximum Tracking Errors with Different Delay Probabilities in Measurement Signals

5. Conclusion and Summary

This paper studies the changes of values of the system transfer matrix situation, analyzed the measurement and control signal random time delay to the ILC convergence speed and the robust convergence effect. By analysis, measurement and control signal of random time delay not only reduces the convergence rate of the system, and affects the system robust convergence and the greater the probability of random time delay, system the slower convergence, the more obvious influence on the system's robust convergence. Especially the control signal of random time delay, its effect on the system robust convergence obviously stronger than the influence of random time delay measurement signals. Finally, through the simulation experiments prove the correctness of the conclusion. In this paper, the analysis is aimed at a class of linear discrete time invariant ILC system, under the condition of satisfy Lipschitz conditions and related assumptions, to the measurement and control of nonlinear discrete random signal delay time-varying ILC System analysis. In addition, the measurement and control signals through wireless network transmission of random time delay and can is multipath, random time delay amount can also be time-varying, such delay impact on the convergence of ILC system remains to be further analysis. In the future, we plan to conduct more theoretical analysis to modify our methodology.

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