Robust Quantized ILC design for Linear Systems Using a 2-D Model

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Abstract: This paper considers the problem of iterative learning control design for linear systems with data quantization, where the system matrices contain uncertain parameters. It is assumed that the control input update signals are quantized before they are transmitted to the iterative learning controller. A logarithmic quantizer is used to decode the signal with a number of quantization levels. Then, a 2-D Roesser model is established to describe the entire dynamics of the ILC system. By using sector bound method, a sufficient asymptotically stability condition for such 2-D system is established and then the ILC design can be given simultaneously. The effectiveness of the proposed method is illustrated by a numerical example.

Key Words: Iterative learning control; 2-D Roesser model; quantization control; robust design

1 INTRODUCTION

Iterative learning control (ILC) is a kind of intelligence control approach. It is an effective technique for systems that could perform same task over a finite time interval repetitively. For such systems, the control input signal is only updated depending on I/O data of previous iteration, and the tracking performance can be improved better than better. Since the first proposed by Arimoto [1], ILC has been widely applied in many practical systems such as robotics, chemical batch processes, hard disk drives and urban traffic systems [2-10].

Recently, network-based control systems (NCSs) have attracted considerable attention from more and more researchers. In NCSs, all devices are connected over a digital communication network. Compare with the classical control theory, the effect of communication network should be considered when studying the problem of controller design for NCSs. The problem of ILC design under the framework of NCSs has received some research attentions. In [11], stochastic iterative learning controllers for the compensation of data dropouts in networked control systems are presented. In [12], an averaging ILC algorithm is proposed for network-based systems subject to one step delay and data dropout. In [13], an H∞ iterative learning controller for a class of discrete-time systems with data dropouts is provided, where the super-vector formulation of such ILC system is established and H∞ performance problem in the iteration domain is defined. In [14], the 2-D model based ILC design has been considered for linear systems with data dropouts, where controller design is transformed into the stabilization of a 2-D stochastic system described by Roesser model. In [15], the iterative learning

control is considered for the networked nonlinear systems with unknown control direction and random packet dropouts.

The results in [11-15] only discuss the network-based ILC systems with packet dropouts. In practical NCSs, owing to the limited transmission capacity of the network, data transmitted should be quantized before they are sent to the next network node. Similar to packet dropout, data quantization is another important issue for NCSs and has been discussed with considerable efforts [16-21]. However, in the ILC field, no paper has been discussed the ILC systems with data quantization except our previous work [22].

In [22], the stability analysis for ILC systems with output measurement quantization is studied. Some stability conditions are given for both linear and nonlinear systems based on contraction mapping approach. It is shown that the tracking error converges to a bound depending on quantization density. That means, when the larger quantization density is chosen, larger tracking error will be produced. Therefore, how to design ILC law can reduce the effect of quantization error is a challenged task. That motivates the present study.

In this paper, we focus on the ILC design for linear systems with signal quantization. The aim of here is to design a novel ILC scheme such that the effect the quantization error can be reduced. We first assume that the control input update signal is quantized before they are transmitted to the iterative learning controller. A logarithmic quantizer is used to decode the signal with a number of quantization levels. Then, a 2-D Roesser system is established to describe the entire dynamics. By using sector bound method to deal with the quantization error, a sufficient asymptotically stability condition for such 2-D system can be established by means of LMI technique and formulas can also be given for the ILC law design simultaneously. The main contribution of this paper is generalized as follows: (1) A novel quantized ILC scheme is proposed, where the control input update signal is first

quantized before entering ILC controller. (2) A 2-D Roesser model is established to describe the entire dynamics of such ILC system. (3) Compare to the existing quantized ILC scheme in [22], the proposed design can guarantee that the tracking error converges to zero.

The rest of this paper is organized as follows. In Section 2, the mathematical description and design objectives are presented. In Section 3, the ILC design is transformed into the stability of an equivalent 2-D Roesser system. A sufficient asymptotic stability condition for such 2-D system is derived, and an ILC design approach can be given based on the condition. The effectiveness and merits of the proposed method are illustrated by a numerical example in Section 4. Finally, the conclusions of this paper are given in Section 5.

2   PROBLEM FORMULATION

Considering the following system with uncertain parameter perturbations

$$\begin{cases} x(t+1,k) = (A+\Delta A)x(t,k) + (B+\Delta B)u(t,k) \\ y(t,k) = Cx(t,k) \end{cases}, \quad (1)$$

where the subscript k denotes iteration, t denotes discrete time. $x(t,k) \in R^n, y(t,k) \in R^l, u(t,k) \in R^m$ are state, input and output variables. The matrices A, B, C are constant matrices with appropriate dimensions. ΔA and ΔB denote admissible uncertain perturbations of matrices A and B, which can be represented as

$$\begin{aligned} \Delta A &= E\Sigma F_1, \\ \Delta B &= E\Sigma F_2, \end{aligned} \quad (2)$$

where E, F_1, F_2 are known real constant matrices characterizing the structures of uncertain perturbations and Σ is an uncertain perturbation of the system that satisfies $\Sigma^T \Sigma \leq I$. The system is operated during a finite time interval $t \in [0, N]$ repetitively.

Basic assumptions for the system are given as follows:

Assumption 1. For a desired trajectory $y_d(t)$, there exists a unique $u_d(t)$ such that

$$\begin{cases} x_d(t+1) = Ax_d(t) + Bu_d(t) \\ y_d(t) = Cx_d(t) \end{cases},$$

where $x_d(t)$ is the desired state.

Assumption 2. The resetting condition is satisfied for all the iteration, i.e.

$$x(0,k) = x_d(0),$$

where $x_d(0)$ is the initial value of the desired state.

For system (1), the control target is to find a control input sequence $u(t,k) = u_d(t)$, such that $y(t,k)$ converges to $y_d(t)$ as $k \to \infty$, i.e., as the learning iteration repeats, the system output converges to the desired trajectory. Considering the following ILC law

$$u(t,k) = u(t,k-1) + r(t,k),$$

where $r(t,k)$ is the updated law.

In most papers, the ILC updated law is often selected as $r(t,k) = f(e(t+1,k), e(t,k), \cdots, e(t-l,k))$, where l is a constant, and then the so-called P-type, PD-type and PID-type ILC can be constructed. Thus, in this paper, we propose the following updated law

$$r(t,k) = K_1\big(x(t,k) - x(t,k-1)\big) + K_2 e(t+1,k-1), \quad (3)$$

where K_1, K_2 are gain metrics to be designed. It can be seen that the above learning law contains the state, tracking error signals of the previous iteration and state signal of the current iteration. This control scheme has the advantages of feedback loop such as robustness and meanwhile enjoys the extra performance improvement from ILC [23, 24].
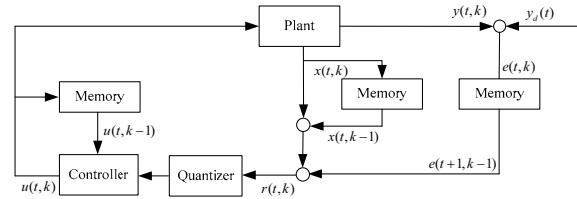

Fig. 1. Block diagram of the ILC system.

As shown in Fig. 1, before entering into the controller, the control input update signal $r(t,k)$ is quantized by quantizer $q(\bullet)$. Then, the ILC update law can be described as

$$u(t,k) = u(t,k-1) + q\big(r(t,k)\big). \quad (4)$$

In this paper, the quantizer $q(\bullet)$ is assumed to be of the logarithmic type and it is defined as

$$q(\bullet) = \big(q_1(\bullet) \quad q_2(\bullet) \quad \cdots \quad q_m(\bullet)\big)^T.$$

For each $q_j(\bullet)$ $(1 \leq j \leq m)$, the set of quantization levels is described by

$$U = \big\{\pm z_i^{(j)} : z_i^{(j)} = \rho_j^i z_0^{(j)}, i = 0, \pm 1, \pm 2, \ldots\big\} \bigcup \{0\},$$
$$0 < \rho_j < 1, z_0^{(j)} > 0.$$

Each of the quantization level corresponds to a segment such that the quantizer maps the whole segment to this quantization level. The logarithmic quantizer $q_j(\bullet)$ is defined as

$$q_j(\bullet) = \begin{cases} z_i^{(j)} & if \ \dfrac{1}{1+\theta_j}z_i^{(j)} < r \leq \dfrac{1}{1-\theta_j}z_i^{(j)} \\ 0 & if \ r = 0 \\ -q_j(-v) & if \ r < 0 \end{cases}, \quad (5)$$

with $\theta_j = \dfrac{1-\rho_j}{1+\rho_j}$.

To this end, the purpose of the problem addressed in this paper is to design ILC gain metrics K_1, K_2, such that the quantized control law (4) can guarantee that $y(t,k)$ converges to $y_d(t)$ as $k \to \infty$.

3   ILC DESIGN

In this section, the sector bound method in [18] is utilized to deal with the quantization error. For the given quantizer $q_j(\bullet)$, a sector-bound expression can be described as $q_j(\bullet) = \left(1 + \Delta_j(r_j)\right)r_j$, where $\left|\Delta_j(r_j)\right| < \theta_j$. Therefore, the quantization effects can be transformed into sector bound uncertainties described above.

Define $\Delta = diag\left(\Delta_1 \quad \Delta_2 \quad \cdots \quad \Delta_m\right)$, the quantizer in ILC law (4) can be described as

$$q\left(r(t,k)\right) = (I + \Delta)r(t,k),$$

then ILC law (4) can be rewritten as

$$u(t,k) = u(t,k-1) + (I + \Delta)K \begin{bmatrix} x(t,k) - x(t,k-1) \\ e(t+1,k-1) \end{bmatrix}. \quad (6)$$

where $K = \begin{bmatrix} K_1 & K_2 \end{bmatrix}$.

Define

$$\eta(t,k) = x(t-1,k+1) - x(t-1,k),$$
$$\delta u(t,k) = u(t,k) - u(t,k-1)$$,

From (1) and (6), we can establish the following 2-D model for the considered ILC system

$$\begin{bmatrix} \eta(t+1,k) \\ e(t,k+1) \end{bmatrix} = \left(\tilde{A} + \tilde{B}\tilde{K}\right) \begin{bmatrix} \eta(t,k) \\ e(t,k) \end{bmatrix}, \quad (7)$$

where

$$\tilde{A} = \overline{A} + \Delta\overline{A}, \tilde{B} = \overline{B} + \Delta\overline{B},$$
$$\overline{A} = \begin{bmatrix} A & 0 \\ -CA & I \end{bmatrix}, \overline{B} = \begin{bmatrix} B \\ -CB \end{bmatrix}, \tilde{K} = (I + \Delta)K$$
$$\Delta\overline{A} = \begin{bmatrix} \Delta A & 0 \\ -C\Delta A & 0 \end{bmatrix}, \Delta\overline{B} = \begin{bmatrix} \Delta B \\ -C\Delta B \end{bmatrix},$$
$$\Delta\overline{A} = \overline{E}\Sigma\overline{F}_1, \Delta\overline{B} = \overline{E}\Sigma\overline{F}_2,$$
$$\overline{E} = \begin{bmatrix} E \\ -CE \end{bmatrix}, \overline{F}_1 = \begin{bmatrix} F_1 & 0 \end{bmatrix}, \overline{F}_2 = F_2.$$

Denoting $\eta(t,k) = X^h(t,k), e(t,k) = X^v(t,k)$, that is

$$\begin{bmatrix} X^h(t+1,k) \\ X^v(t,k+1) \end{bmatrix} = A_X \begin{bmatrix} X^h(t,k) \\ X^v(t,k) \end{bmatrix}, \quad (8)$$

where $A_X = \tilde{A} + \tilde{B}\tilde{K}$.

We know that system (8) is a typical 2-D Roesser system. The synthetic for ILC system under the control law (6) is equivalent to the stabilization of Roesser's system. Now, we first give the stability definition for the 2-D system.

Definition 1[25]: For any bounded initial boundary condition, if $\lim_{t,k \to \infty} X(t,k) = 0$ is satisfied, then the 2-D system (8) is said to be asymptotically stable.

The following lemmas are used to obtain our main result.

Lemma 1[25]: The 2-D system (8) is asymptotically stable if there a block diagonal matrix $P = diag\left\{P_1, P_2\right\} > 0$, where $P_1 \in R^{n \times n}, P_2 \in R^{m \times m}$, such that
$$A_X^T P A_X - P < 0.$$

Lemma 2: Assume X, Y are matrices or vectors with appropriate dimensions. For any scalar $\varepsilon > 0$ and all matrix Ω with appropriate dimensions satisfying $\Omega\Omega^T \leq I$, the following inequality holds:
$$X\Omega Y + Y^T \Omega^T X^T \leq \varepsilon X X^T + \varepsilon^{-1} Y^T Y.$$

Remark 1: As stated in [25], the boundary condition of 2-D system is defined as

$$X_{0,0} = \begin{pmatrix} X^h(0,0)^T & X^h(0,1)^T & X^h(0,2)^T & \cdots, \\ X^v(0,0)^T & X^v(1,0)^T & X^v(2,0)^T & \cdots \end{pmatrix}$$

According to the assumption 2, we can obtain $\eta(0,k) = 0$ for all k. Meanwhile, since the control input at first iteration $u(t,0)$ is given with a bounded value, the tracking error $e(t,0) = y_d(t) - Cx(t,0)$ is also bounded. Therefore, the bound boundary condition of 2-D system (8) is satisfied.

Now, we can give our main result.

Theorem 1. If there exist a block diagonal matrix $P = diag\left\{P_1, P_2\right\} > 0$, where $P_1 \in R^{n \times n}, P_2 \in R^{m \times m}$, matrices W and two positive constant η, σ such that the following LMI holds

$$\begin{bmatrix} -Q \\ \overline{A}Q + \overline{B}W & -Q + \sigma\overline{E}\overline{E}^T \\ 0 & \eta\overline{B}^T & \eta I + \sigma\overline{F}_2^T\overline{F}_2 \\ \Lambda W & 0 & 0 & \eta I \\ \overline{F}_1 Q + \overline{F}_2 W & 0 & 0 & 0 & \sigma I \\ 0 & \eta\overline{E}^T & 0 & 0 & 0 & \sigma I \end{bmatrix} < 0, \quad (9)$$

then, the 2-D system (7) is asymptotically stable. Furthermore, if this condition is hold, a suitable gain matrix of ILC law (4) can be given by $K = WQ^{-1}$.

Proof. Using Schur complement, the condition in lemma 1 can be rewritten

$$\begin{bmatrix} -P & * \\ \tilde{A} + \tilde{B}\tilde{K} & -P^{-1} \end{bmatrix} < 0. \quad (10)$$

Define $\Omega = \Delta\Lambda^{-1}$, , it is obvious that $\Omega\Omega^T = \Omega^T\Omega \leq I$. Substituting $\tilde{K} = (I + \Delta)K$ into (10), we can obtain

$$M + X\Omega Y + Y^T\Omega^T X^T < 0, \quad (11)$$

where

$$M = \begin{bmatrix} -P & * \\ \tilde{A} + \tilde{B}K & -P^{-1} \end{bmatrix}, X = \begin{bmatrix} 0 \\ B \end{bmatrix}, Y = \begin{bmatrix} \Lambda K & 0 \end{bmatrix}.$$

By applying Lemma 2 and Schur complement to (11), we can obtain

$$\begin{bmatrix} -P & & & \\ \tilde{A} + \tilde{B}K & -P^{-1} & & \\ 0 & \bar{B}^T & \varepsilon I & \\ \varepsilon \Lambda K & 0 & 0 & \varepsilon I \end{bmatrix} < 0.$$

Define $Q = P^{-1}, \eta = \varepsilon^{-1}$, by applying congruence transformation $diag(Q, I, \eta I, \eta I)$ on (12) yields

$$\begin{bmatrix} -Q & & & * \\ \tilde{A}Q + \tilde{B}KQ & -Q & & \\ 0 & \eta \bar{B}^T & \eta I & \\ \Lambda KQ & 0 & & \eta I \end{bmatrix} < 0. \quad (12)$$

Setting $KQ = W$ and Substituting $\tilde{A}, \tilde{B}$ into (12), we can obtain

$$\begin{bmatrix} -Q & & & * \\ \bar{A}Q + \bar{B}W & -Q & & \\ 0 & \eta \bar{B}^T & \eta I & \\ \Lambda W & 0 & & \eta I \end{bmatrix}$$
$$+ \begin{bmatrix} 0 \\ \bar{E} \\ 0 \\ 0 \end{bmatrix} \Sigma \begin{bmatrix} \bar{F}_1 Q + \bar{F}_2 W & 0 & 0 & 0 \end{bmatrix} + \left(\begin{bmatrix} 0 \\ \bar{E} \\ 0 \\ 0 \end{bmatrix} \Sigma \begin{bmatrix} \bar{F}_1 Q + \bar{F}_2 W & 0 & 0 & 0 \end{bmatrix} \right)^T$$
$$+ \begin{bmatrix} 0 \\ 0 \\ \bar{F}_2^T \\ 0 \end{bmatrix} \Sigma \begin{bmatrix} 0 & \eta \bar{E}^T & 0 & 0 \end{bmatrix} + \left(\begin{bmatrix} 0 \\ 0 \\ \bar{F}_2^T \\ 0 \end{bmatrix} \Sigma \begin{bmatrix} 0 & \eta \bar{E}^T & 0 & 0 \end{bmatrix} \right)^T < 0,$$

$$(13)$$

Using Lemma 2, we know that the following inequality is a sufficient condition for (13)

$$\begin{bmatrix} -Q & & & * \\ \bar{A}Q + \bar{B}W & -Q & & \\ 0 & \eta \bar{B}^T & \eta I & \\ \Lambda W & 0 & & \eta I \end{bmatrix}$$
$$+ \sigma \begin{bmatrix} 0 \\ \bar{E} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} 0 & \bar{E}^T & 0 & 0 \end{bmatrix} + \sigma^{-1} \begin{bmatrix} (\bar{F}_1 Q + \bar{F}_2 W)^T \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} \bar{F}_1 Q + \bar{F}_2 W & 0 & 0 & 0 \end{bmatrix}$$
$$+ \sigma \begin{bmatrix} 0 \\ 0 \\ \bar{F}_2^T \\ 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & \bar{F}_2 & 0 \end{bmatrix} + \sigma^{-1} \begin{bmatrix} \eta \bar{E} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} 0 & \eta \bar{E}^T & 0 & 0 \end{bmatrix} < 0.$$

$$(14)$$

Note that (14) is equivalent to

$$\begin{bmatrix} -Q & & & & * \\ \bar{A}Q + \bar{B}W & -Q + \sigma \bar{E}\bar{E}^T & & & \\ 0 & \eta \bar{B}^T & \eta I + \sigma \bar{F}_2^T \bar{F}_2 & & \\ \Lambda W & 0 & & \eta I \end{bmatrix}$$
$$+ \sigma^{-1} \begin{bmatrix} (\bar{F}_1 Q + \bar{F}_2 W)^T & 0 \\ 0 & \eta \bar{E} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \bar{F}_1 Q + \bar{F}_2 W & 0 & 0 & 0 \\ 0 & \eta \bar{E}^T & 0 & 0 \end{bmatrix} < 0$$

Using Schur complement for the above condition, we can obtain the theorem 2.

This completes the proof.

Remark 2: Theorem 1 provides a sufficient condition for the asymptotic stability of 2-D systems. Under this condition we can obtain $\lim_{t,k \to \infty} X(t,k) = 0$, which means $\lim_{k \to \infty} e(t,k) = 0$. Hence, the proposed ILC algorithm can obtain zero tracking error. As pointed in [22], the P-type ILC only guarantee bound convergence and the bound of tracking error depends on quantization error. Hence, the proposed ILC design can obtain better tracking performance than quantized ILC algorithm in [22].

4 NUMERICAL EXAMPLE

In this section, a numerical example is given to illustrate the proposed results. Considering the following SISO linear system

$$\begin{cases} x(k,t+1) = \left(\begin{bmatrix} -0.8 & -0.22 \\ 1 & 0 \end{bmatrix} + \Delta A \right) x(k,t) \\ \qquad + \left(\begin{bmatrix} 0.5 \\ 1 \end{bmatrix} + \Delta B \right) u(k,t), \\ y(k,t) = \begin{bmatrix} 1 & 0.5 \end{bmatrix} x(k,t), \end{cases} \quad (15)$$

where $\Delta A, \Delta B$ indicates uncertain parameter perturbation caused by nonlinearity of the system or model mismatch and they are assumed to be non-repeatable.

The desired output is given as

$$y_d(t) = \sin(\frac{8}{50}t) + \sin(\frac{4}{50}t), t \in [0,100].$$

For the initial state, it is assumed that $x(0,k) = x_d(0) = 0$ for all k. The ILC law is applied by adopting the zero initial control input $u(t,0) = 0$ for all $t \in [0,100]$. The parameters in the quantizer is chosen as $z_0 = 3, \delta = 0.8$, then $\theta = 0.11$. The proposed designs are illustrated with the following two different cases of uncertainty. For simplicity, it is assumed that uncertain parameter perturbation randomly changed from iteration to iteration. That is

$$E = \begin{bmatrix} 0.1 & 0.1 \\ 0 & 0 \end{bmatrix}, F_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, F_2 = \begin{bmatrix} 0.05 \\ 0.05 \end{bmatrix},$$

$$\Sigma = \begin{bmatrix} \xi_1(k) & \\ & \xi_2(k) \end{bmatrix}, \left|\xi_1(k)\right| < 1, \left|\xi_2(k)\right| < 1,$$

where $\xi_{1,2}(k)$ are unknown variables. In simulation, $\xi_{1,2}(k)$ are assumed to be random variables which are uniformly distributed within interval $[-1,1]$. With the above parameters, we apply the controller design method in Theorem 2. The corresponding controller gains are computed as $K_1 = [-0.21 \quad 0.15], K_2 = 0.68$.

Fig. 2 shows the system output trajectory at 20th iteration, where the solid line denotes actual system output and the dot line denotes desired trajectory. To validate the effective of the proposed algorithm, the P-type ILC algorithm in [22] is also simulated to make a comparison. The system outputs at 20th iteration of P-type ILC algorithm is shown in Fig. 3. The tracking errors for the two ILC algorithms are also given in Fig. 4. It can be seen that the tracking error of the proposed algorithm can tend to zero and the perfect tracking performance can be obtained after 20th iteration. However, the tracking error of P-type ILC in [22] could not reduce to zero due to the effect of quantization error.
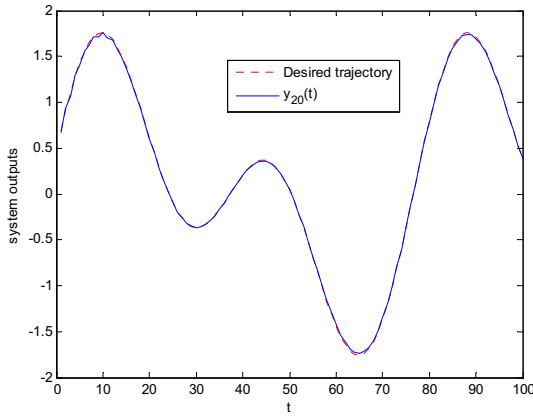

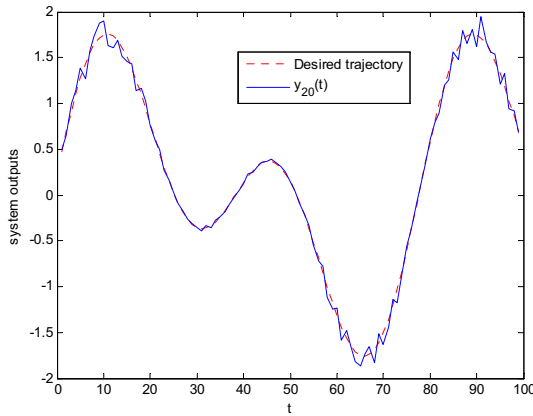Fig.2 The tracking performance at 20th iteration

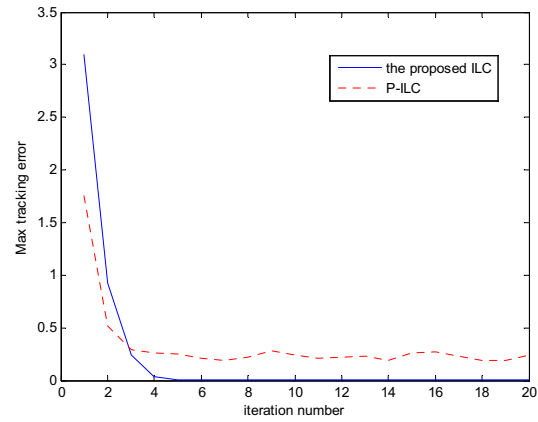Fig.3 The tracking performance at 20th iteration using P-ILC algorithm

Fig.4 The max tracking errors

5 CONCLUSIONS

In this paper, we have discussed the ILC design for linear systems with signal quantization. A new ILC law using both state signal and tracking error signal has been proposed with a logarithmic quantizer. The 2-D Roesser model has been established to describe the ILC dynamics. By using sector bound method to deal with the quantization error, a sufficient asymptotically stability condition for such 2-D system has been given by means of LMI technique and formulas can also be given for the ILC law design. It is shown that the tracking error of the ILC system can converge to zero by using the proposed design. In future work, we will discuss the monotonic convergence ILC design for such systems.

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