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LMI based nonlinear Iterative Learning Control for uncertain discrete repetitive system

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Conflicts of Interest
There are no conflicts to declare.

ABSTRACT

The problem encountered in this paper is to design a robust, feedback-based improved control system for the plant that involves systematic uncertainty. This paper proposes a fault estimation algorithm based on iterative learning control. This algorithm is constructed through an optimization function to prove the robustness and convergence of the algorithm. Through linear matrix inequality (LMI), the observer gain matrix and iterative learning parameter matrix in the algorithm are solved. The two comprehensive parameters in LMI represent the parameter selection in the two specifications to make selected adjustments in learning and control. A numerical example shows the improvement process and the effectiveness of these methods. Through LMI techniques, we have obtained satisfactory results and controller stability and robustness against fault-tolerant control. Lastly, the simulation results show the effectiveness and accuracy of the proposed algorithm.

Keywords: REPETITIVE CONTROL SYSTEMS, NONLINEAR UNCERTAINTIES, FAULT ESTIMATION, ITERATIVE LEARNING CONTROL, FAULTS-TOLERANT CONTROL, LINEAR MATRIX INEQUALITY (LMI)

1- Introduction

The iterative learning control problem itself has a strong engineering background. Therefore, only discussing the convergence of the algorithm without external disturbances cannot meet the application requirements. We should also fully study the convergence of the system under external disturbances. Tracking effect. In an actual running iterative learning control system, in addition to the disturbance of the initial state value, there are also external periodic or non-periodic disturbances such as measurement noise and input noise. The problem of robustness is to discuss the tracking ability of the iterative learning control algorithm when there are various disturbances in the operating cycle of the system. It was mentioned in the literature [1] that the robustness of a system means that the system output under the control of the controller can converge to a neighborhood of the expected output under bounded external disturbances. When these disturbances disappear completely, the system will converge to the desired output [2].

Respective control (RC) is a real approach to deal with and/or resist constantly repetitive signals from different places over time. A repetitive control system replacing the control set CR(s) will generate infinite feedback oscillations at the basic frequency of the regular signal and higher harmonics [3, 4]. This ensures that the output actually has no static errors at all [5, 6].

In control theory, the RC is a neutral-type delay, the number is like endless Poles. In 1988, "Scientific American" (English) mentioned that RCs can only stabilize unless there are zero degree relative plants. The most technicians, need to push the low-level filter on the delay control for a strictly proper plant. On this basis, the established system is improved to modify RCs (MRCs) and its low-level filter can reduce the steady state at the cost of high-frequency tracking signals. That is to say, the stability and tracking functions in MRC have an intermediate point. Therefore, on the one hand, it is a stable system, and on the other hand, it is easily introduced into the distorted system when there is great uncertainty in the way [7, 8].

Iterative learning control was first proposed by Japanese scholar Uchiyama in 1978 [9]. This control theory was proposed when he studied the control strategy of the motion state of the manipulator in industrial production. However, he did not use English to show this to the world. A pioneering scientific research result, so it has not attracted the attention of the international academic community. It was not until 1990 that Arimoto [10] and others clarified the concept of iterative learning control, and further promoted and improved the theory, which attracted widespread international attention.

ILC is like learning to control repeatedly (ILC), which is alternative famous method that uses previous control tries [11]. It is used for repeated tasks. (She and his team 2012; Liu, Chow, and Chen 2013) investigated that ILC keeps same starting conditions in each period [12-15]. The beginning of the RC state is equal to the final state of the system in the previous trial. Fundamentally re-adjusting the different initial conditions brings unlike analysis techniques and results.

RC includes the fact that there are two measures to continuously control repetitive process and the discrete one. In reality, the words "control" and "learn" mean that we utilize data different from the current and earlier times to yield control input. The Control input design methods that allow prioritized adjustment of control and learning may improve convergence and improved performance [16, 17]. Most of the design approaches designed for one-dimensional, time domain mainly emphasis on the stability of the system. They snub the difference between these two behaviors and only deliberate their whole impact. Therefore, the gun power in the gun is difficult to greatly improve. A better solution is to use the second-degree force (2D) system theory (Bose 2003) in order to design a robust RCS. Contrary to these methods, the neutral 2d method gives us the casual solution to regulate control and learning. The perfectly executed system has appropriate robustness, and the controlling ability is also very good [14, 18, 19].

ILC uses the tracking error and unique data of the system to continuously adjust the current input target, so that the system output can quickly track the expected output within a limited time [11, 20-22]. Based on iterative learning control system can be regarded as a form of repeated processes based on batch axis and the timeline, the system control problem of the research in recent years, came to the attention of academia at home and abroad, and successfully used in multi-axis truss type robot, injection molding machine and electric motorcycle motor system in the practical repeat operations such as industrial object [2, 23-25]. As the process of industrialization continues to accelerate, industrial systems are becoming more and more complex, and people's requirements for system reliability and safety are getting higher and higher, making fault diagnosis and fault-tolerant control (FTC) in the past few decades [26-29]. Both academic and practical application fields have received more and more attention. Fault-tolerant control is divided into two categories one is active and another is passive fault-tolerant control. In fact, most researches pay more attention to active fault-tolerant control. Fault estimation [30-33] is different for fault diagnosis, it can accurately estimate the magnitude and shape of the fault, thereby reconstructing the fault signal. Therefore, in many existing literature, fault estimation is a prerequisite for fault tolerance control, and has achieved an affluence of theoretical research results [34-36].

A class of iterative learning fault-tolerant control problems for uncertain discrete nonlinear repetitive processes with unknown actuator faults is studied. By designing the iterative learning fault-tolerant control law and defining the hybrid Lyapunov function based on the iteration and the time axis, the stability of the system under normal and fault conditions is discussed, respectively, and the sufficient settings for the presence of robust fault-tolerant controllers are based on LMI is given. Through the application simulation experiment of the speed control system, the efficacy of the algorithm is verified.

1- Problem description

Consider the following class of uncertain discrete time invariant nonlinear systems running repeatedly:

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

Where, $k = 0,1... N$ stands for batch, and the repeating time cycle within each batch is 0≤t≤T. X (t, k)∈Rn, u $(t, k) \in R^{l}$, $y(t, k) \in R^{m}$ separately symbolize the state vector, input vector and output vector of the system. Without loss of generality, suppose the initial boundary conditions of the system x(0, k) = x0, u(t, 0) = u0(t). Matrix A, B and C are respectively the corresponding dimension of the system matrix, Δ A, Δ B and C Δ said uncertainty [37] and satisfy the following relations: Δ A = H1 Ξ F1, Δ B = H1 Ξ F2, Δ C = H2 Ξ F2, including H1, H2, F1 and F2 to already know the certainty of the matrix, Ξ Ξ T Ξ I or less bounded constraint condition.

Therefore, discrete time invariant nonlinear system (1) with actuator fault can be stated as

$$\begin{cases} x(t+1,k)=(A+\Delta A)x(t,k)+(B+\Delta B)\omega t(t,k)+ \\ \qquad f(x(t,k)) \\ y(t,k)=(C+\Delta C)x(t,k) \end{cases} \quad (2)$$

Containing actuator faults of uncertain discrete nonlinear time invariant system (7), the control target of this article is in unknown actuator failure under the condition of meet the condition (6), based on the iterative learning fault-tolerant control input, made the control system output $y\ (t,\ k)$ can be gradually with the increase of batches to trace the desired output $y_d\ (t)$, i.e.

$$\sup_{0\le i\le T} (y_x(t)-y(t,k)| < \varepsilon$$

2- ILC controller design

The vital and main role of this study is to track the output error $e(t,\ k)$, which can be distinct as follows:

$$e(t,\ k) = y_k(t) \text{-} y(t,\ k) \quad (3)$$

For the system (7), the following control law is designed:

$$u(t,k+1) = u(t,k) + \Delta u(t,k+1) \quad (4)$$

Where, $u(t,\ k\ +1)$ is the system control input of the current batch; $u(t,\ k)$ is the control input of the previous batch; $\Delta\ u\ (t,\ k\ +\ 1)$ is to modify control system input amount of updates.

For the convenience of analysis, define:

$$\begin{cases} \hat{\eta}(t+1,k+1) = x(t,k+1) - x(t,k) \\ \hat{\varphi}(t,k+1) = f(x(t-1,k+1)) - f(x(t-1,k)) \end{cases} \quad (5)$$

Therefore, the modified update quantity in iterative learning control law (9) can be further obtained as

$$\Delta u(t,k+1) = K_1\hat{\eta}(t+1,k+1) + K_2 e(t+1,k) \quad (6)$$

Where, K1 and K2 are unknown undetermined matrices.

By substituting the iterative learning fault-tolerant control law form (4) into the nonlinear system (1), the state space model of discrete repeated processes can be obtained in the following form:

$$\begin{cases} \hat{\eta}(t+1,k+1) = A\hat{\eta}(t,k+1) + Be(t,k) + \\ \qquad \varphi(t,k+1) \\ e(t,k+1) = C_{\eta}(t,k+1) + De(t,k) + \\ \qquad k_{\varphi}(t,k+1) \end{cases} \quad 7)$$

In which,

$$\begin{aligned} A &= (A+\Delta A) + (B+\Delta B)\alpha K_1 \\ B &= (B+\Delta B)\alpha K_2 \\ C &= -(C+\Delta C)\left((A+\Delta A) + (B+\Delta B)\alpha K_1\right) \\ D &= I - (C+\Delta C)(B+\Delta B)\alpha K_2 \\ E &= -(C+\Delta C) \end{aligned}$$

Obviously, discrete repetitive process model (7) is a nonlinear repeated process, including $\boldsymbol{\eta}(t+1,k+1)$ and $\mathbf{e}(t,\mathbf{k})$, respectively, represents the time and batch variable on the axis direction, $\boldsymbol{\varphi}(t,\mathbf{k}+1)$ is to enter the present process of iterative nonlinear input item, conventional stability analysis of linear systems of KYP lemma methods cannot be directly used to solve the repetitive process system with nonlinear term.

3- Simulation Experiment

The robust fault-tolerant topology is applied on speed control of the rotation control system. The system is composed of two DC motors, one is the controlled entity and the other is the interfering generator as shown in Figure 1. The shafts of the two motors are coupled together by springs and are continuously executed as shown in Figure 1 and the parameters are given in Table 1. The system state equation is as follows:

$$A = \begin{bmatrix} -\frac{K_p^2}{J_p R_p} & 0 & -\frac{K_{pd}}{J_p} \\ 0 & -\frac{K_d^2}{J_d R_d} & \frac{K_{pd}}{J_d} \\ 1 & -1 & 0 \end{bmatrix}$$
$$B = \begin{bmatrix} \frac{K_p}{J_p R_p} \\ 0 \\ 0 \end{bmatrix} B_d = \begin{bmatrix} 0 \\ \frac{K_d}{J_d R_d} \\ 0 \end{bmatrix} C = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}^{\mathrm{T}} \quad (8)$$

The following Table-1 shows the detail of the parameters and their numerical values. The system parameters with their SI units explained as:

Table 1: Parameters for the proposed control plant

parameters	Symbol	Units
Applied voltage	u	$Volt(V)$
Disturbance voltage	d	$Volt(V)$
Armature current	$\tau_p(\tau_d)$	$Ampere(A)$
Torque produced	$i_p(i_d)$	$Newton\_meters(Nm)$
Twisting torque	τ_{pd}	$Newton\_meters(Nm)$
Rotational speed	$\omega_p(\omega_d)$	$Radians/\sec ond(rad/s)$
Rotation angle	$\theta_p(\theta_d)$	$Radians/(rad)$
Inertia	$J_p(J_d)$	$(K.gm^2)$
Resistance of armature coil	$R_p(R_d)$	$Ohms(\Omega)$
Back-electromotive-force constant	$K_p(K_d)$	(Vs/rad)
Twisting elasticity coefficient of coupling	K_{pd}	(Nm/A)

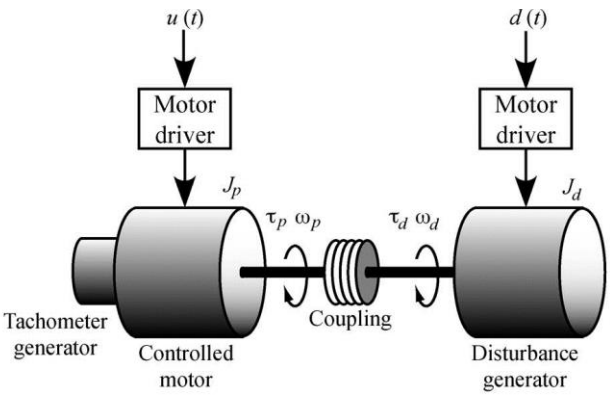

Figure 1: Block diagram of a rotational control system

$$A = \begin{bmatrix} -31.31 & 0 & -28330 \\ 0 & -10.25 & 8001 \\ 1 & -1 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 28.06 \\ 0 \\ 0 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$$

For the parameters in Table-1, the mat laboratory toolbox creates a feasible solution for LMI . After that, take out the calculation from equation 8, we can put in the following:

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

The rotating system takes 400s as a cycle running time, and the system is discretized with a sampling time of = 0.01s, and considering the disturbance of the state and the output terminal, the matrix parameters of the discrete state space of the rotating system in the arrangement of equation (1) can be obtained as follows :

At time t∈ [0, 400], the initial state of each batch is 0. Suppose the system's operating frequency norm $[0,\infty]$ is divided into $[0,\infty]$ = [0, 6] ∪[6, 25] ∪ $[25,\infty]$. After the 20th iteration, the occurrence actuator's fault suddenly appears, and the fault in the system is $f(t)=0.32\sin(\pi t)+0.4\sin(2\pi t)$. Evaluate performance and introduce performance indicators: $y_d(t)=\sin(\pi t)+0.5\sin(2\pi t)+0.5\sin(3\pi t)$

$$\text{RMS}(e(t,k))=\sqrt{\frac{1}{400}\sum_{t=1}^{400}\text{e}^2(t,k)}$$

Supposing that the coefficients of matrices A and B contain uncertainties, the decomposition of the uncertainty is carried out as follows: If the uncertainty matrix of the system H1= [-0.05, 0.1] , H2= [-0.12， 0.15], F1= I , F2=$[1,1]^T$ $\Xi=diag\{\sigma_1,\sigma_2\}$, σ1, and σ2 are -1 ~ 1 Then, the gain matrix of the fault-tolerant controller are K1= [-1.6349， 1.8293], K2=[2.1291].

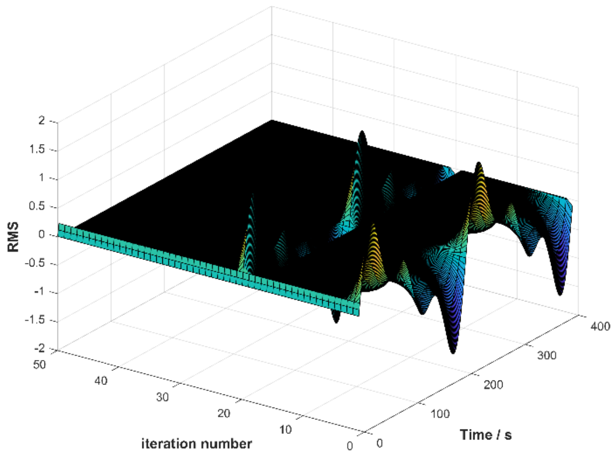

Figure 2: RMS error without uncertainty

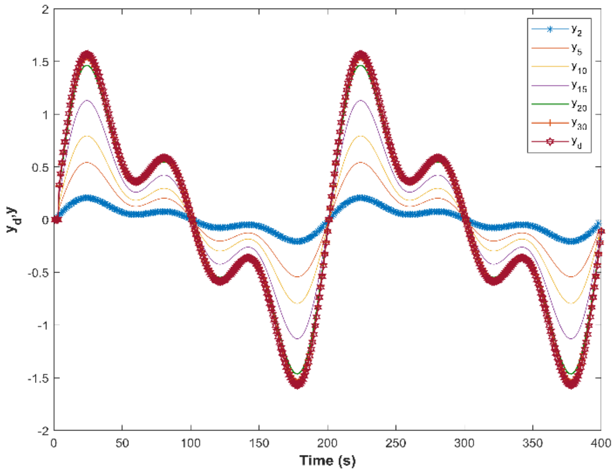

Figure 3:Reference VS desired trajectory for different iterations with uncertainty

The simulation outcomes and effects of the control law are shown in Figure 2 and Figure 4. Even with non-repetitive disturbances, the tracking error of the first 20 batches of the system before the failure occurred quickly converged to a stable state with respect to time, and the tracking performance continued to improve in the batch direction, as shown in Figure 2; in the 25th batch of process failures. After it happened, the tracking performance of the system was lower than that of the 25th batch. However, after several batch iterations, the tracking performance reached an ideal level again, as shown in Figure 3. This conclusion is reflected in Figure 3 and Figure 4. Figure 3 shows the daily values of different batches, and Figure 4 shows the tracking error of the system in a three-dimensional graph.

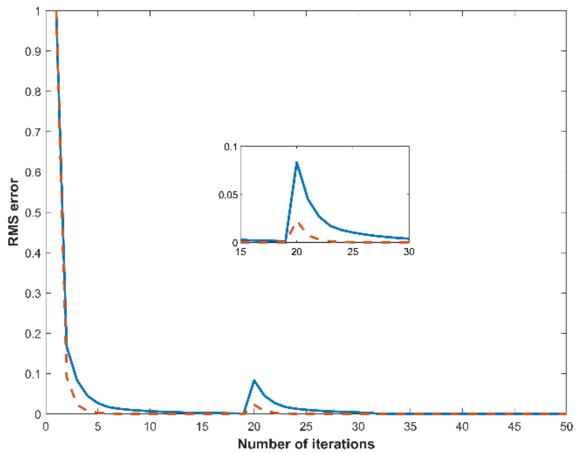

Figure 4: Error convergence with and without uncertainty

Figure 2 - Figure 4 shows that under the use of time-varying faults and non-repetitive disturbances, the proposed algorithm can guarantee monotonic convergence of the system in both batch and time directions under normal and fault scenarios, and it is asymptotically stable. The designed controller has both fault-tolerant and fault-tolerant performances, and has a robust suppression effect on non-repetitive external interference.

4- Conclusion

This paper research objective was the linear repetitive process affected by external disturbances, discusses the passive fault-tolerant control of the system, designs a robust iterative learning FTC algorithm based on 2D system theory, and analyzes the stability and performance of the system using LMI technology. Sufficient conditions for robust performance under unknown disturbances, and the convex optimization problem is used to obtain the controller parameters that make the system perform optimally in the two directions of time and batch. Finally, the application simulation experiment of the rotation speed control system shows the effectiveness of the proposed algorithm.

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