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Iterative learning controller design for nonlinear generalized distributed parameter system with correction factor

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Iterative learning control techniques are suitable for systems or devices that run over a limited time interval repeatedly. These include manipulators, disk drives, and inverter circuits. Under the premise that the initial error is zero, the tracking error can be zero everywhere. This applies to the whole operation interval after several iterations. In practical applications however, the initial error is zero, which is difficult to achieve. In order to widen the application scope of iterative learning control technology in practical industrial applications, it is necessary to study the suitable iterative learning control method under the condition of non-zero initial error. In this paper, an iterative learning control (ILC) method for initial correction of state-constrained reference signals for nonparametric a class of generalized distributed parameter systems is proposed. This method is suitable for the case of a non-zero initial error. By tracking the zero error of the system state to the corrected reference signal in the whole operation interval, the zero error tracking of the system state to the reference signal is obtained. According to the characteristics of generalized distributed parameter system, this paper uses the principle of singular value decomposition. First, the singular value decomposition of the generalized distributed parameter system is carried out. Secondly, an iterative learning PD-type learning law with correction factor is designed. Then its convergence is proved theoretically and strictly proved by Bell-Grown theory. The convergence condition is given. Finally, the algorithm is simulated by numerical simulation. The simulation results show that the algorithm is effective.

Keywords: Nonlinear generalized distributed parameter systems; iterative learning control; correction factor

1. INTRODUCTION

Iterative learning control (ILC) is an advanced intelligent algorithm, and has a strong engineering background. It was proposed by Arimoto[1-2] in 1984. So far, more and more people have applied this algorithm to the control of repetitive motion in the last three decades. At present, iterative learning control has always been a research hotspot [3-8].

The initial learning control - Iterative Learning Control (ILC) was initiated by Japanese scholars in 1978. Unlike other control methods starting from linear controlled objects, iterative learning control takes the nonlinear system as the research object, and the control task of output full tracking is implemented on the finite interval [0,T]. Here perfect tracking refers to the output of the system from start to finish, whether it is transient or steady state and is consistent with the target track. Obviously, the starting point of iterative learning control is higher than other control methods. From the development history of 20 years, the starting point is too high and there are two disadvantages: 1) the lack of development space and 2) difficulty of integration with mainstream control

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methods.

In fact, as long as the task is repeatable, or the system interference is periodic, ILC can be used to solve the actual problem. It has been developed from the generation of iterative learning control methods for more than 20 years. It has developed into a new development direction in the field of intelligent control. Its research has nonlinear, strong coupling, difficult modeling and high-precision trajectory control. This a very important question for research to resolve.

Iterative learning control is applied to controlled systems with repetitive motion properties, and its goal is to achieve full tracking tasks on finite intervals. It tries to control the controlled system and corrects the undesired control signal with the deviation of the output signal from the given target, so that the tracking performance of the system can be improved. The study of iterative learning control is very important for dynamic systems with strong nonlinear coupling, high positional repeatability, difficult modeling and high-precision trajectory tracking control requirements. Its form is

$$U_{p+1}(t) = U_p(t) + K * E_p$$

where $U_p(t)$ is the input to the system during the p_{th} repetition, E_p is the tracking error during the p_{th} repetition and K is a design parameter representing operations on E_p. Achieving perfect tracking through iteration is represented by the mathematical requirement of convergence of the input signals as p becomes large whilst the rate of this convergence represents the desirable practical need for the learning process to be rapid. There is also the need to ensure good algorithm performance even in the presence of uncertainty about the details of process dynamics. The operation is crucial to achieving design objectives and ranges from simple scalar gains to sophisticated optimization computations [33−36].

Singular distributed parameter systems are more widely used than general distributed parameter systems[39−46], such as cable signal propagation, temperature distribution, heat exchange, heat flow, image processing, waveguide line, weak decoupling system and voltage distribution in electromagnetic coupling superconducting lines. They are essentially different from the general distributed parameter systems. When under disturbance, the structure of the system can change dramatically. With the rapid development of science and technology, the research on this system is becoming more and more important.

The research study of generalized distributed parameter systems has only about ten years. In this period, the main problems are related to three aspects:

1) Modeling problem

It can be seen from the forming process of singular distributed parameter system, the different research fields of scholars constantly improve the mathematical models established in understanding natural phenomena and natural laws with mathematical tools in order to achieve a more realistic description. How to establish a generalized distributed parameter system model for describing natural phenomena and natural laws is still an important issue to be studied.

2) Problems of solutions for generalized distributed parameter systems

In 1988, Kaczorek[9-10] studied the solvability of discrete models, and gave the necessary conditions for the existence of solutions to singular distributed parameter systems; In 1990, Lewis[11] studied the problem of solving singular distributed parameters and gave the numerical solution. In 1991[12-13], Lewis et al. used 2-D theory and Z transform and gave the solution of the discrete model; the same year, Joder [14] gave the numerical solution of the singular distributed parameter system described by the singular parabolic equation. So far, there is still a lot of work to be done about the solution of generalized distributed parameter system. Obviously, this is a complicated problem. Whether it can establish a new semigroup theory to study the solution of singular distributed parameter system is a further research question that needs to be examined.

3) Control issues

In 1993, Ge[15] has studied a class of singular distributed parameter systems and gives sufficient conditions for the stabilization of the system in Hilbert space. In 1994[14], he also studied the pole assignment problem of the system. By using the generalized inverse of the bounded linear operator in Hilbert space, a constructive expression of control volume was given. Yinjun Zhang [16] discussed iterative learning control for singular distributed parameter system with forgetting factor including a time-delay. In 1999, Yang and Liu[17] studied the variable structure control design method of singular distributed parameter systems described by generalized parabolic equations. In the same year, Yang[18] also made a robust stabilization control design of the system by using the intrinsic function method, but the design process is complicated and the control needs to set an infinite number of switching equipment. Liu Feng[19] discussed feedback stabilization for a class of second order singular distributed parameter system in Hibert space. It can be seen from the above literature that Ge has laid a good foundation for the development of a generalized distributed parameter system. So GE proposed GE-semigroup theory in 2013[35−38].

In the past few years, the theoretical research of SDPS has attracted more and more attention from scholars. Current research on SDPS mainly focuses on two aspects. In an expression and characteristic considering the solution, for example, literature [17] shows the solution of a coupled hyperbolic partial differential equation with a singular matrix coefficient from the Fourier method. In the literature [18,19], we introduce the operator decomposition method and empathy to discuss the solvability of homogeneous constant SDPS in Banach space. The boundary value problem is concerned with linear SDPS and [4]'s variables separation method and matrix theory. On the other hand, it is a study of its control problems, for example, in [20], the robust exponential stability of uncertain SDPS under linear operator inequality is studied. Based on the method of the generalized operator semigroup theory and the function analysis method combined with the mean residence time, the synthesis of SDPS in the Hilbert space, including the feedback stability and the well posed problem, is given some sufficient conditions in [21-23]. In document [24], we study the sliding mode control scheme of SDPS with perturbation using the intrinsic function method. In document [25], a state feedback control method is proposed for parabolic SDPS, and the equivalent decomposition form is given based on spectrum analysis. In short, SDPS's control theory combines singular system theory with distributed parameter system theory [26-28]. The ILC study of singular systems and DPS is limited, and only some related results are reported. Document [29] uses the Laplasse transform to design the P type ILC renewal law of linear non-uniform DPS in frequency domain. The ILC scheme based on the characteristic spectrum is considered for semi linear DPS, and the Galerkins model and the characteristic spectrum theory are applied to reduce the [30] model. In the literature [31,32], we give the P algorithm with the convergence conditions of the closed loop and open-loop uncertain linear DPS respectively using the contraction mapping principle. [33] uses the Frobenius norm to solve the ILC tracking problem of the fast subsystem of the singular system with pulse behavior and the requirements of the pulse controlled constraint. The PD type ILC law of singular discrete systems is given by using singular value decomposition transformation in [34-36]. However, according to the author, there is no report on the ILC of parabolic type SISO SDPS.

However, most of the existing research results about singular distributed parameter system just discussed the stabilization and feedback control issues in Hilbert space, there is not much literature on iterative learning control for GDPs.

Iterative learning control techniques are suitable for systems or devices that run repeatedly over a limited time interval, such as manipulators, disk drives, and inverter circuits. Under the premise that the initial error is zero, the tracking error can be zero everywhere in the whole operation interval after several iterations. However, in practical applications, the initial error is zero. This is difficult to achieve. In order to widen the application scope of iterative learning control technology in practical industrial applications, it is necessary to study the suitable iterative learning control method under the initial error condition of a non-zero value.

In this paper, an iterative learning control (ILC) method for initial correction of state-constrained reference signals for nonparametric uncertain systems is proposed. This method is suitable for the case of non-zero initial error. By tracking the zero error of the system state to the corrected reference signal in the whole operation interval, the zero error tracking of the system state to the reference signal is obtained.

In order to improve the robustness and security of the system, a new iterative learning controller is adopted to constrain the system state in each iteration. In this paper, the construction scheme of the modified reference signal, the design of the controller and the convergence analysis of the closed-loop system are given, and the effectiveness of the proposed control method is verified by numerical simulation.

2. SOME DEFINITIONS[27-29]

A SDP system (relative the SLP system) is an infinite-dimensional system in the state space. Therefore, such a system is also called an infinite dimensional system. A typical example is a system described by a partial differential equation or a delayed differential equation.

Here are some general mathematical symbols used in this paper. $L^2(\Omega)$ (or short in L^2) represents a kind of Ω function space consisted by all measureable functions and it is bounded, satisfying $u_p = \left\{\int_\Omega |u(x)|^p dx\right\}^{1/p} < \infty \quad (1 \le p \le \infty)$. $L^p(\Omega)$ is Banach space, $L^2(\Omega)$ is Hilbert space. For the dimensional vector $u = \left(u_1^T, u_2^T, \cdots, u_i^T\right)$, where the norm of definition is $\|u\| = \left(\sum_{i=1}^{n} u_i^2\right)^{1/2}$. If $u_i(x) \in L^2$, $i = 1, 2, \cdots, n$ then $Q(x) = (Q_1(x), Q_2(x), \cdots, Q_n(x)) \in R^n \cap L^2$, and $\|Q\|_{L^2} = \left\{\int_\Omega \left(Q^T(x) Q(x)\right)^2 dx\right\}^{1/2}$. For the function $f(x,t) \quad \Omega \times [0,T] \to R^n$, $f(\cdot,t) \in R^n \cap L^2$, $t \in [0,T]$ define its $\left(L^2, \lambda\right)$ norm as follows $\|f\|_{(L^2,\lambda)} = \sup_{0 \le t \le T} \left\{\left(\|f\|_{L^2}^2\right) e^{-\lambda t}\right\}$.

3. NEW PROBLEM STATEMENT

Consider the following nonlinear generalized distributed parameter system based on singular value decomposition.

$$\begin{cases} \bar{E}\dot{x}_n(t) = \bar{A}x_n(t) + f(t, x_n(t)) + Bu_n(t) \\ y_{nk}(t) = C(t)x_{nk}(t) \end{cases} \tag{1}$$

where k is iterative times, $x_{nk}(t) \in R^1$, $y_{nk}(t) \in R^r$, $u_{nk}(t) \in R^m$ are state vector, output vector and control input respectively. $\bar{A} \in R^{m\times l}$, $B(t) \in R^{l\times m}$ are constant matric, and $\bar{E} \in R^{1\times 1}$ is singular matrix. f is a nonlinear mapping vector with corresponding dimensions.

This paper will use the following assumptions:

(1) The nonlinear mapping vector f satisfies the Lipschitz condition with interval $t \in 0, T \perp$, the constant is k_f;

(2) The system is reachable, we can find arbitrary desired control input $u_{nd}(t)$ corresponding to expected output $y_{nd}(t)$.

$$\begin{cases} \bar{E}\dot{x}_{nd}(t) = \bar{A}x_{nd}(t) + f(t, x_{nd}(t)) + Bu_{nd}(t) \\ y_{nd}(t) = C(t)x_{nd}(t) \end{cases} \tag{2}$$

(3) When the system is running iteratively, the initial value of the system should satisfy

$$x_{nk}(0) = x_n^0, \; k = 1, 2, 3, \ldots \tag{3}$$

For the system(1), the paper proposed the closed-loop PD-type learning law

$$u_{nk+1}(t) = u_{nk}(t) + q(\dot{e}_{nk+1}(t) + L(t)e_{nk+1}(t) + \gamma(t)) \tag{4a}$$

where $L(t)$ is learning gain, $\gamma(t)$ is initial correction factor

$$\gamma(t) = e^{-Lt}\eta_g(t)(y_{nd}(0) - Cx_n^0) \tag{4b}$$

where $\int_0^g \eta_g(s)dts = 1$, when $t \ge h$ or $t \le 0$, $\eta_g(t) = 0$, g is time regulator, and $\bar{E} + \bar{B}(t)q(t)C(t)$ is reversible.

Convergence analysis of systems with correction factor

For the above assumptions 1,2 and 3, we will analyze the convergence of the system.

The theorem 1. for the above assumptions 1–3, the system will satisfy the convergence condition with the learning law (4)

$$\sup_{t\in 0,T} ||I-\tilde{B}|| \le \varepsilon_1 < 1 \tag{5}$$

If all of the above hold as true, the output of the system $y_{nk}(t)$ can converge to the expected output $y_{nd}(t)$ under the learning control law (4) when $k \to \infty$.

$$\lim_{n\to\infty} y_{nk}(t) = \tilde{y}_{nk}(t)$$

where $\tilde{y}_{nd}(t) = y_{nd} + e^{-Lt}(Cx_{n0} - y_{nd}(0))$,

$$\tilde{y}_{nd}(t) = \begin{cases} y_{nd}(t) - e^{-Lt}(y_{nd}(0) - Cx_{n0}) \\ \quad \left(1 - \int_0^t \eta_g(s)ds\right), t \in 0, g \\ y_{nd}(t),\ t \in g, T \end{cases} \tag{6}$$

Proof. For the system described in Eq. 1, we give the initial state x_n^0 when the control input of the system is $\tilde{u}_{nd}(t)$, then the ideal output trajectory of system is $\tilde{y}_{nd}(t)$.

We introduce the following remark.

$$\begin{aligned}
\partial\tilde{u}_{nk}(t) &= \tilde{u}_{nd}(t) - u_{nk}(t) \\
\partial\tilde{x}_{nk}(t) &= \tilde{x}_{nd}(t) - x_{nk}(t) \quad \tilde{e}_{nk}(t) = y_{nd}(t) - \tilde{y}_{nd}(t) \\
e_{nk}(t) &= \tilde{e}_{nk}(t) + e^{-Lt}(y_{nd}(0) - Cx_n^0) \\
&\quad - e^{-Lt}(y_{nd}(0) - Cx_n^0)\int_0^t \eta_g(s)ds
\end{aligned}$$

Then

$$\begin{aligned}
e_{nk+1}(t) &= \tilde{e}_{nk+1}(t) + e^{-Lt}(y_{nd}(0) - Cx_n^0) \\
&\quad - e^{-Lt}(y_{nd}(0) - Cx_n^0)\int_0^t \eta_g(s)ds
\end{aligned}$$

So its derivative is

$$\begin{aligned}
\dot{e}_{nk}(t) &= \dot{\tilde{e}}_{nk}(t) + e^{-Lt}(y_{nd}(0) - Cx_n^0) \\
&\quad \left(1 - \int_0^t \eta_g(s)ds\right) - \gamma(t) \qquad (7) \\
\dot{e}_{nk+1}(t) &= \dot{\tilde{e}_{nk+1}} + e^{-Lt}(y_{nd}(0) - Cx_n^0) \\
&\quad \left(1 - \int_0^t \eta_g(s)ds\right) - \gamma(t) \qquad (8)
\end{aligned}$$

According to the learning law(4), we know

$$\begin{aligned}
\partial\tilde{u}_{nk+1}(t) &= \partial\tilde{u}_{nk}(t) - q(\dot{e}_{nk+1}(t) + L(t)e_{nk+1}(t) + \gamma(t)) \\
&= \partial\tilde{u}_{nk}(t) - q(\dot{\tilde{e}}_{nk+1}(t) + e^{-Lt}(y_{nd}(0) - Cx_n^0) \\
&\quad \left(1 - \int_0^t \eta_g(s)ds\right) - \gamma(t)) \\
&\quad - qL(t)(\tilde{e}_{nk+1}(t) + e^{-Lt}(y_{nd}(0) - Cx_n^0) \\
&\quad - e^{-Lt}(y_{nd}(0) - Cx_n^0)\int_0^t \eta_g(s)ds) - q\eta(t) \\
&= \partial\tilde{u}_{nk}(t) - q\dot{\tilde{e}}_{nk+1}(t) - qL(t)\tilde{e}_{nk+1}(t) \\
&= \partial\tilde{u}_{nk}(t) - qC\dot{\tilde{x}}_{nk+1}(t) - qL(t)\partial\tilde{x}_{nk+1}(t)
\end{aligned} \tag{9}$$

Equation (1) is subtracted from equation (2) and deformation, we can get

$$\begin{aligned}
&(\bar{E}(t) + \bar{B}(t)q(t)C(t))\dot{\tilde{x}}_{nk+1}(t) \\
&= (\bar{A}(t) - \bar{B}(t)q(t)L(t)C(t))\partial\tilde{x}_{nk}(t) \\
&\quad + f(x_{nd}(t)) - f(x_{nk+1}(t)) + \bar{B}(t)\partial\tilde{u}_{nk}(t)
\end{aligned} \tag{10}$$

According to the above conditions, $(\bar{E}(t) + \bar{E}(t)q(t)C(t))$ is reversible.

$$\begin{aligned}
&(\bar{E}(t) + \bar{B}(t)q(t)C(t))^{-1} = p(t), \\
&p(t)(\bar{A}(t) - \bar{B}(t)q(t)L(t)C(t)) = \tilde{A}(t), \\
&p(t)\bar{B}(t) = \tilde{(}t),
\end{aligned}$$

So the Eq. 10 can be transformed

$$\begin{aligned}
\dot{\tilde{x}}_{nk+1}(t) &= \tilde{A}(t)\partial\tilde{x}_{nk+1}(t) + p(t) \\
&\quad (f(x_{nd}(t) - f(x_{nk+1}(t))) + \tilde{B}(t)\partial\tilde{u}_{nk}(t)
\end{aligned} \tag{11}$$

Integrating (11) from 0 to t and using the initial condition, we get

$$\begin{aligned}
\tilde{x}_{nk+1}(t) &= \int_0^t \tilde{A}(t)\partial\tilde{x}_{nk+1}(\tau)d\tau \\
&\quad + \int_0^t p(t)(f(x_{nd}(\tau)) - f(x_{nk+1}(\tau)))d\tau \\
&\quad + \int_0^t \tilde{B}(t)\partial\tilde{u}_{nk}(\tau)d\tau
\end{aligned} \tag{12}$$

Taking the norm of (12) yields

$$\begin{aligned}
||\tilde{x}_{nk+1}(t)|| &\le (p + k_f + a)\int_0^t ||\partial\tilde{x}_{nk+1}(\tau)||d\tau \\
&\quad + b\int_0^t ||\partial\tilde{u}_{nk}(\tau)||d\tau
\end{aligned} \tag{13}$$

where $\sup_{t\in 0,T} ||p(t)|| = p$, $\sup_{t\in 0,T} ||\tilde{A}(t)|| = a$, $\sup_{t\in 0,T} ||\tilde{B}(t)|| = b$.

According to Bell-Grown formula yields

$$||\tilde{x}_{nk+1}(t)|| \le b\int_0^t e^{(p+k_f+a)(t-\tau)}||\partial\tilde{u}_{nk}(\tau)||d\tau \tag{14}$$

Introducing (11) to (9) yields

$$\partial\tilde{u}_{nk+1}(t) = (I - \tilde{B}(t))\partial\tilde{u}_{nk}(t) - (q(t)L(t)C(t) + qC\tilde{A})\partial\tilde{x}_{nk+1}(t) - p(t)(f(t, x_{nd}(t)) - f(t, x_{nk+1}(t))) \quad (15)$$

Taking the norm of (15), we have

$$||\partial\tilde{u}_{nk+1}(t)|| \leq ||(I - \tilde{B}(t))||\,||\partial\tilde{u}_{nk}(t)|| + ||(q(t)L(t)C(t) + qC\tilde{A})||\,||\partial\tilde{x}_{nk+1}(t)|| + ||p(t) + k_f||\,||\partial\tilde{x}_{nk+1}(t)|| \quad (16)$$

Remark

$$\sup_{t\in 0,T} ||(I - \tilde{B}(t))|| = \varepsilon,$$

$$\sup_{t\in 0,T} ||q(t)L(t)C(t) + qC\tilde{A} + pk_f|| = m_1$$

So (16) can be rewritten

$$||\partial\tilde{u}_{nk+1}(t)|| \leq \varepsilon||\partial\tilde{u}_{nk}(t)|| + m_1||\partial\tilde{x}_{nk+1}(t)|| \quad (17)$$

Introducing (14) to (17) yields

$$||\partial\tilde{u}_{nk+1}(t)|| \leq \varepsilon||\partial\tilde{u}_{nk}(t)|| + m_1 b\int_0^t e^{(p+k_f+a)(t-\tau)}||\partial\tilde{u}_{nk}(\tau)||d\tau \quad (18)$$

When both sides of (18) are multiplied by $e^{-\lambda t}$ we get

$$||\partial\tilde{u}_{nk+1}(t)||e^{-\lambda t} \leq \varepsilon||\partial\tilde{u}_{nk}(t)||e^{-\lambda t} + m_1 b\int_0^t e^{(p+k_f+a)(t-\tau)}e^{-\lambda(\tau-t)} e^{-\lambda t}||\partial\tilde{u}_{nk}(\tau)||d\tau \quad (19)$$

According to the λ norm definition, and rearrange the (19) we have

$$||\partial\tilde{u}_{nk+1}(t)||_\lambda \leq \left(\varepsilon - m_1 b\frac{1 - e^{p+k_f+a-\lambda}T}{p + k_f + a - \lambda}\right)||\partial\tilde{u}_{nk}(t)||_\lambda \quad (20)$$

Remark $\left(\varepsilon - m_1 b\frac{1-e^{(p+k_f+a-\lambda)T}}{p+k_f+a-\lambda}\right) = \hat{\varepsilon}$, if we choose the sufficient λ, and because of $\varepsilon \in 0, 1)$, then $\hat{\varepsilon} \in 0, 1)$, so we know that (20) is mapping of $||\partial u_{nk}(t)||_\lambda$,
And we can obtain

$$\lim_{k\to\infty} ||\partial\tilde{u}_{nk}(t)||_\lambda = 0 \quad (21)$$

The same can be obtained

$$\lim_{k\to\infty} ||\partial\tilde{e}_{nk}(t)||_\lambda = 0 \quad (22)$$

so

$$\lim_{k\to\infty} y_{nk}(t) \to \tilde{y}_{nd}(t) \quad (23)$$

QED.

4. SYSTEM NUMERICAL ANALYSIS

Consider the following limited nonlinear generalized distributed parameter systems with repetitive property.

$$\begin{cases} \bar{E}x_n(t) = \bar{A}x_n(t) + f(t, x_n(t)) + Bu_n(t) \\ y_{nk}(t) = C(t)x_{nk}(t) \end{cases}$$

where

$$E = \begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}, \quad \bar{A} = \begin{bmatrix}0 & 1\\-2 & -3\end{bmatrix}$$

$$B = \begin{bmatrix}0\\1\end{bmatrix}, \quad C = [0\ 1]$$

We give the desired trajectory $y_{n1d}(t) = 0.25t^2 + \sin 2t$, $y_{n2d}(t) = 0.25t^2 + e^{3t}$. The initial state of the system at each iteration is $x_{nk}(0) = 0.5$, the learning gain $q = 1$, $L = 6$. the index function $G_k = \max_{0.4\leq x\leq 5}|e_{nk}(t)|$ if defined. The comparison of the simulation results of the first component of the system is shown in figures 1 and 2. From the simulation results, we can see that the convergence speed of the PD learning algorithm with correction factor (MPD) proposed in this section is better than that of the ordinary PD learning algorithm. Figures 3 and 4 reflect the tracking and G_k values of the second component system.

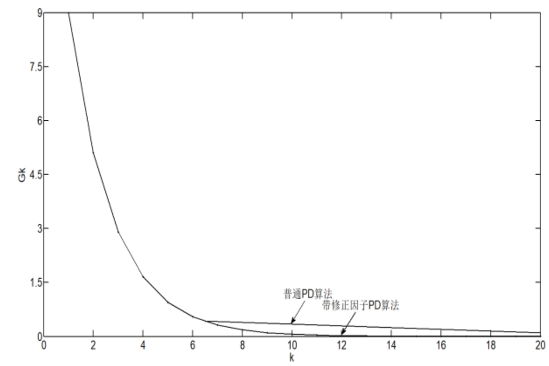

Figure 1 General PD learning law and Gk value under the learning control (MPD) system with initial correction factor.

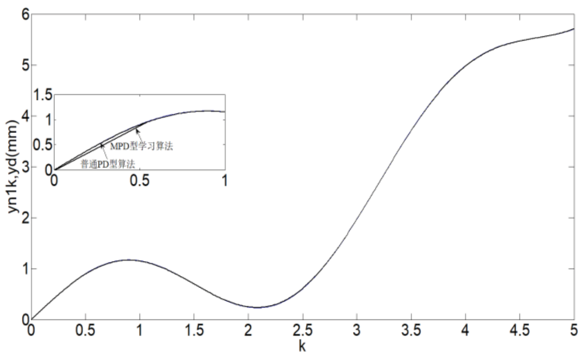

Figure 2 The output of the ordinary PD learning law and the MPD with the 20 iterations.

The above analysis and simulation results show that the learning rate is obviously accelerated after adding the correction factor, and the learning law can guarantee convergence to zero in finite time when adjusting the gain. That is to say, it can achieve complete consistent tracking in finite time domain. This fully demonstrates the effectiveness of the algorithm.

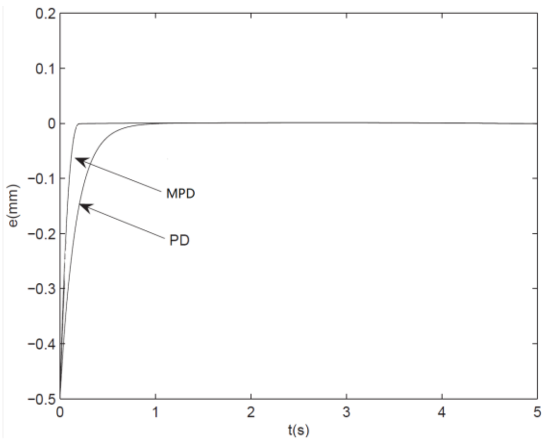

Figure 3 Tracking error of general PD learning law and learning law with modified factor when k=20.

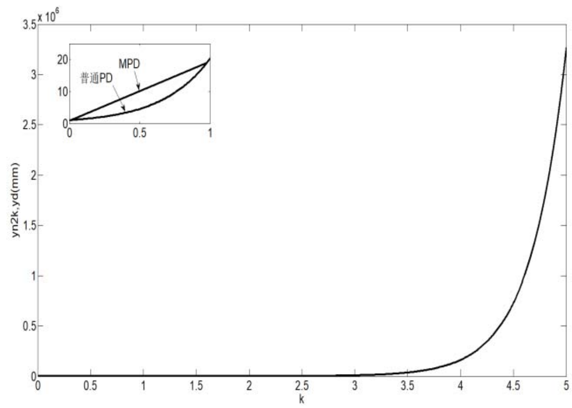

Figure 4 General PD learning law and system output under the modified law of learning when k=20.

From the above analysis, the system can still track the desired trajectory when the parameters of the learning law with correction factors change. This can be obtained in future proofs.

5. CONCLUSIONS AND OUTLOOK

Starting from the principle of a class of nonlinear generalized distribution parameters, the first and second components are obtained on the basis of singular value decomposition. The convergence of the system is proved theoretically.

In order to improve the robustness and security of the system, a new type of PD controller with correction factor is used to design the controller, which constrains the state of the system during each iteration. In this paper, the construction scheme of the modified reference signal, the design of the controller and the convergence analysis of the closed-loop system are given, and the effectiveness of the proposed control method is verified by numerical simulation.

At present, there is no relevant literature to discuss the iterative learning control problem of nonlinear generalized distributed parameter systems. The work done in this paper has theoretical significance as well as practical value. We also hope that our future research work will have some theoretical guiding significance for the future.

Of course, our current work is still very limited, and future research and discussion should focus on such aspects as time delay.

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Authors' contributions

All authors contributed equally and significantly in writing this article. All authors read and approved the final manuscript. Yinjun Zhang is the corresponding author.

Compliance with ethical standards

Conflict of interests The authors declare that there is no conflict of interests regarding the publication of this paper.

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