선형 파라미터화된 시스템에 대한 적분형 적응보상기

An Integration Type Adaptive Compensator for a Class of Linearly Parameterized Systems

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요 약

본 논문은 선형적으로 파라미터화된 시스템에 대한 보상방식을 제안한다. 이 보상기는 전형적인 선형 제어기와 적분형의 적응법칙을 갖는 적응 관측기로 구성되며 이 때 적응법칙은 SG 알고리즘에 근거하여 설계된다. 제안된 보상전략에서는 다른 여러 연구에서 제안된 중간함수 대신에 growth조건, convex조건, attainability조건, 그리고 pseudo gradient 조건을 만족하는 함수들로 적응법칙이 설계된다. 제안된 방식은 추적오차에 대한 점근적 안정도 및 파라미터에 대한 추정오차의 bounded stability를 만족한다. 예제를 통하여 제안된 보상방식의 타당성을 보인다. 그리고 기존의 방식인 Huang의 방법과의 비교를 통해 제안된 방식이 정상상태에서의 파라미터 오차가 더 작아짐을 보인다.

Abstract

A compensation scheme for a class of linearly parameterized systems is presented. The compensator consists of a typical linearizing control and an adaptive observer with integration type update law, which is based on Speed Gradient (SG) algorithm. Instead of the intermediate functions of the compensation schemes suggested by other researchers, the proposed compensator is designed with some design functions which guarantee the growth, convexity, attainability, and pseudo gradient conditions in the update law. The scheme achieves the asymptotic stability of the tracking error and the boundedness of the estimation errors. A numerical example is given to demonstrate the validity of the proposed design.

Key words : Adaptive compensator, Speed gradient algorithm, Convexity.

I. Introduction

Parameter uncertainty is unavoidable in the control of a dynamical system, which may degrade the tracking performance of systems. This effect is originated from the lack of precise knowledge of the system parameters and/or external structured disturbance. In practice, unfortunately, parameter uncertainty is a natural phenomenon that is extremely difficult to model. Hence, compensating the uncertainty based on the adaptive estimation in control systems is required. Therefore diverse compensation schemes for the uncertainty have been developed in recent decade [1-7]. These works focus on canceling the friction by applying some control force if the accurate friction models are available. Specifically, it is first noted that the adaptive observer in [1] fulfilled that need for a servo system with Coulomb friction. The method is restricted to the condition that the magnitude of the velocity is bounded away from zero. The restrictive condition was relaxed and systematically selection of the intermediate nonlinear function of velocity, $g(|x_2|)$ was proposed based on a Lyapunov scheme in [3]. However the estimator of the method also needs some conditions for the function $g(|x_2|)$. Liao and Chien proposed an exponentially stable adaptive friction compensator [5] in which the condition for the function

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[3] and [5], however, the transient response of the estimators are influenced by the selection of the intermediate function.

For further extensions, an adaptive compensation design for a class of linearly parameterized systems was proposed in [8]. Huang [8] suggested an adaptive compensator for a class of linearly parameterized systems, which is a generalized version of [1], [3], and [5]. In that work, the compensator consists of a typical linearizing control and an adaptive observer for online estimation of the system's parameters, including the friction as well as other parameter uncertainties, which achieves the asymptotic stability of tracking and estimation error dynamics. However, the transient response of the estimator is also influenced by the selection of the intermediate functions $g_i(x(t))$ and needs a condition for a gain function $q(x)$ in $g_i(x(t))$.

In this paper, an adaptive compensator for a class of linearly parameterized system is proposed based on speed gradient algorithm (SG) suggested by Fradkov [12-13]. The proposed estimator need not the intermediate nonlinear function and has an integration type update law which is constructed by some design functions. These designed functions satisfy the pseudo gradientity condition and growth, convexity, attainability conditions, respectively. The proposed scheme provides an asymptotic stability for system tracking error based on the aim function and the boundedness of the estimation errors by Lyapunov direct method. A case study via simulation is undertaken to demonstrate its validity and the comparisons with the proposed method and the Huang's method are given.

The paper is organized as follows. Section 2 reviews some preliminary results of [1], [3], [5], and [8]. Section 3 presents the integration type adaptive compensation strategy based on SG algorithm. Section 4 provides some simulation results on a single-mass servocontrol system and the comparisons of the proposed method with the Huang's method are given. Conclusions are finally made in Section 5.

II. Review of Adaptive Compensation

Consider a class of linearly parameterized systems described by

$$\begin{aligned} \dot{x}_1 &= x_2 \\ &\vdots \\ \dot{x}_{n-1} &= x_n \\ \dot{x}_n &= u - F(\theta,x) \end{aligned} \tag{1}$$

where $x=[x_1,x_2,\cdots,x_{n-1},x_n]^T \in R^n$ is the system state vector; $u \in R$ is the control input; $F(\theta,x) \in R$ is the unknown structured uncertainty and $\theta \in R^r$ is the unknown parameter vector. In the rest of this note, $F(\theta,x)$ is assumed to be expressible as a linear combination of a set of *known* basis functions, i.e.,

$$F(\theta,x) = \theta^T \phi(x) = \sum_{i=1}^{r} \theta_i \phi_i(x) \tag{2}$$

where $\phi_i(x), i=1,\cdots,r$ are the corresponding basis functions of the regressor vector $\phi(x)$. Meanwhile, $\phi(x)$ is assumed to be continuously differentiable in x and is bounded for bounded states. It is noted that the expression in (2) covers a wide variety of applications.

Given a desired trajectory $x^d(t)=[x_1^d,\cdots,x_{n-1}^d,x_n^d]^T$, the control objective is to drive $x(t) \to x^d(t)$ as $t \to \infty$ and to identify θ correctly. A typical linearizing control [8] for $u(t)$ in (1) is adopted

$$u(t) = \dot{x}_n^d + k^T e + \hat{\theta}^T(t)\phi(x) \tag{3}$$

where $e = x - x^d$ is the tracking error vector; $k=[k_1,\cdots,k_n]^T$ is the control gain vector; and $\hat{\theta}(t)$ is the estimated parameter vector for θ at the time t. Define the estimation error vector $\tilde{\theta}(t)=\hat{\theta}(t)-\theta$. In terms of $e(t)$ and $\tilde{\theta}$, the state-space representation of the system (1) under the control (3) can be written as

$$\dot{e} = Ae + B\tilde{\theta}^T \phi(x) \tag{4}$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & 1 \\ -k_1 & -k_2 & -k_3 & \cdots & -k_n \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \tag{5}$$

where $A \in R^{n \times n}$, $B \in R^{n \times 1}$.

Friedland and Park [1] consider the second-order system with only Coulomb friction, i.e.,

$$F(\theta,x) = \theta sgn(x_2), \tag{6}$$

where $\theta \in R$ is the Coulomb friction coefficient. A structure of the estimator proposed in [1] is as follows:

$$\hat{\theta} = z - g(|x_2|) = z - \alpha |x_2|^{\mu} \quad (7)$$

where $\alpha > 0, \mu > 0$ are the positive design parameters selected to achieve a proper transient response, $g(|x_2|)$ is a nonlinear function of $|x_2|$, and z denotes an intermediate variable whose dynamics is chosen as

$$\dot{z} = \alpha\mu |x_2|^{\mu-1}(u - \hat{\theta} sgn(x_2)) sgn(x_2). \quad (8)$$

A linearizing feedback control for this control system is then designed on the basis of the estimated parameter $\hat{\theta}$ and given by

$$u = \dot{x}_2^d - k^T e + \hat{\theta}(t) sgn(x_2). \quad (9)$$

The above estimator design, however, only results in *conditional* asymptotic stability of the error dynamics. That is, the error dynamics is asymptotically stable, provided velocity is always bounded away from zero [2].

Yazdizadeh and Khorasani [3] proposed a Lyapunov-based method to systematically select the nonlinear function $g(|x_2|)$ and relax the condition imposed in [1]. In that study, the second-order system with only Coulomb friction as (6) considered. That work relaxed the constraint on the velocity of [1] and provided some certain criteria for selecting the nonlinear function used in the nonlinear estimator. The proposed adaptive estimator in [3] is given by

$$\hat{\theta} = z - g(|x_2|) \quad (10)$$

and

$$\dot{z} = g'(|x_2|)(u - \hat{\theta} sgn(x_2)) sgn(x_2) \quad (11)$$

where $g'(|x_2|)$ denotes the derivative of $g(|x_2|)$ with respect to $|x_2|$. The nonlinear function $g(|x_2|)$ is selected on the basis of the following two-criterion [3]: 1) $g(|x_2|)$ is monotonically increasing and 2) $0 < g'(|x_2|) < K_{max}$ for all $|x_2| \geq 0$. In that case, the linearizing feedback control is designed by (9).

Liao and Chien [5] suggested an exponentially stable adaptive compensator for the same system as (6). The proposed adaptive estimator in [5] is given by (10) and

$$\dot{z} = g'(|x_2|)(u - \hat{\theta} sgn(x_2)) sgn(x_2) + 2e^T PB sgn(x_2) \quad (12)$$

where P is a symmetric and positive-definite matrix; i.e., $P = P^T > 0$, and is a solution of the following Lyapunov equation:

$$A^T P + PA = -Q = -I_2 \quad (13)$$

where I_2 is 2-dimensional identity matrix. Moreover, the nonlinear function $g(|x_2|)$ satisfies the following condition:

$$0 < K_{\min} \leq g'(|x_2|) \leq K_{\max} \quad \text{for all } |x_2| \geq 0. \quad (14)$$

In that case, the linearizing feedback control is designed by (9).

Huang [8] proposed an adaptive compensator for a class of linearly parameterized systems, which is a generalized version of [1], [3], and [5]. In that work, the compensator consists of a typical linearizing control and an adaptive observer for online estimation of the system's parameters, which achieves the asymptotic stability of tracking and estimation error dynamics under the condition that the basis functions $\phi_i(x), i = 1, \cdots, r$ in the regressor vector are linearly independent in terms of the desired states. The suggested estimator in [8] is given by

$$\hat{\theta}_i(t) = z_i(t) - g_i(x), \quad i = 1, \cdots, r \quad (15)$$

and

$$\dot{z}_i(t) = \frac{\partial g_i(x)}{\partial x_n}\left(u(t) - \hat{\theta}^T \phi(x)\right) + \sum_{j=1}^{n-1} \frac{\partial g_i(x)}{\partial x_j} x_{j+1} - e^T PB\phi_i(x), \quad i = 1, \cdots, r \quad (16)$$

where the matrix $P \in R^{n \times n}$ is the solution to the Lyapunov equation of (13). Since the matrix A is Hurwitz, a symmetric positive definite matrix P can always be solved. Meanwhile, the functions $g_i(x)$, $i = 1, \cdots, r$ are given by

$$g_i(x(t)) = \int_{x_n(t_0)}^{x_n(t)} q(x_1, \cdots, x_{n-1}, \xi)\phi_i(x_1, \cdots, x_{n-1}, \xi) d\xi, \quad i = 1, \cdots, r \quad (17)$$

where $q(x)$ is a gain function satisfying the following criterion:

$$0 < q(x) < K_{\max}, \quad \forall x \in R^n. \tag{18}$$

In [8], $q(x)$ was selected by $q(x) = 1$.

III. An Integration Type Adaptive Compensator

In this section we derive an adaptive compensator for a class of linearly parameterized system. Before developing the adaptive compensator, we introduce a theorem for convex function. The proposed compensation scheme is based on speed gradient(SG) algorithm suggested by Fradkov, which needs the growth, convexity and attainability conditions.

Definition 1. Let S be a convex set in R^n and let $f: S \to R^1$ be a real-valued function. We say that f is a convex function on S if and only if $f[\lambda x_1 + (1-\lambda)x_2] \le \lambda f(x_1) + (1-\lambda) f(x_2)$ for all $x_1, x_2 \in S$ and for all λ such that $0 \le \lambda \le 1$.
Note that convex functions are not defined if the domain is not a convex set.

Theorem 1. Let S be a convex set in R^n and suppose that $f: S \to R^1$ is convex. Let x^0 be an interior point of S.
(a) Then there are real numbers $a_1, a_2, \cdots, a_n$ such that

$$f(x) \ge f(x^0) + \sum_{i=1}^{n} a_i (x_i - x_i^0), \quad \text{for } x \in S \tag{19}$$

(b) If $f \in C^1$, i.e., first derivative of function f is continuous, on $S^{(0)}$, where $S^{(0)}$ denotes the set of interior points of S, then

$$a_i = \left. \frac{\partial f}{\partial x_i} \right|_{x = x^0}, \quad i = 1, \cdots, n. \tag{20}$$

Proof : See [15].

In general error dynamics of adaptive control system is a nonlinear differential equation and can be expressed as

$$\dot{e}(t) = \Xi(e, \tilde{\theta}, t), \quad t \ge 0, \tag{21}$$

where $e(t) \in R^n$ is an error state vector, $\tilde{\theta}(t) \in R^r$ is a parameter estimation error vector, $\tilde{\theta}(t) = \hat{\theta}(t) - \theta$, $\Xi(\cdot) : R^{n+r+1} \to R^n$ is a continuously differentiable vector function in x, θ.
The compensation problem is to find the parameter update law

$$\hat{\theta}(t) = \Theta(e_0^t, \hat{\theta}_0^t, t) \tag{22}$$

according to some criterion of "good" function of the system, where notation e_0^t and $\hat{\theta}_0^t$ mean the set $\{e(s), 0 \le s \le t\}, \{\hat{\theta}(s), 0 \le s \le t\}$, respectively.

Suppose this criterion requires to provide low values of some aim function $Q_t = Q(e_0^t, \hat{\theta}_o^t, t)$. Typically Q_t may have local form such as $Q_t = Q(e(t), t)$, where $Q(e(t), t) \ge 0$ is a scalar smooth aim function. Let us define a function $w(e, \hat{\theta}, t)$ as time derivative of Q_t. Then

$$w(e, \hat{\theta}, t) = (\nabla_e Q)^T \Xi(e, \hat{\theta}, t) + \nabla_t Q \tag{23}$$

where $\nabla_e Q$ and $\nabla_t Q$ denote the gradients of Q in e and t, respectively.

With the above definition, we propose the parameter update law for compensating system (21),

$$\hat{\theta}(t) = -\psi(e, \hat{\theta}, t) - \Gamma \int_0^t \nabla_{\hat{\theta}} w(e, \hat{\theta}, s) ds \tag{24}$$

where Γ is a symmetric positive definite matrix, $\psi(\cdot)$ satisfies pseudo gradientity condition, i.e., $\psi(e, \hat{\theta}, t)^T \nabla_{\hat{\theta}} w(e, \hat{\theta}, t) \ge 0$, where $\nabla_{\hat{\theta}} w$ denotes the gradient of w in $\hat{\theta}$.

Theorem 2 : [12-13] Let system (21) and (24) have unique solution for any initial conditions $e(0)$, $\hat{\theta}(0)$, and functions $\Xi(e, \hat{\theta}, t)$, $\nabla_e Q(e, t)$, $\psi(e, \hat{\theta}, t)$, $\nabla_{\hat{\theta}} w(e, \hat{\theta}, t)$ be locally bounded in t (bounded in some region $\{(e, \hat{\theta}, t) : \|e\| + \|\hat{\theta}\| \le \beta \le \infty, \text{ for } t \ge 0\}$) and following condition be held:

1) Growth condition : $\inf_t Q(e, t) \to \infty$ as $\|e\| \to \infty$.
2) Convexity condition : $w(e, \hat{\theta}, t)$ is convex in $\hat{\theta}$.
3) Attainability condition : vector $\theta \in R^r$ and a function $\rho(Q)$ exists such that $\rho(Q) > 0$ when $Q > 0$ and

$$w(e, \theta, t) \le -\rho(Q). \tag{25}$$

Then all solutions of system (21), (24) are bounded and $Q_t \to 0$ as $t \to \infty$.

Proof : The proof is based on the Lyapunov-like function

$$V_t = Q_t + \frac{1}{2}\left(\hat{\theta}(t) - \theta + \psi(e,\hat{\theta},t)\right)^T \Gamma^{-1}\left(\hat{\theta}(t) - \theta + \psi(e,\hat{\theta},t)\right) \quad (26)$$

By convexity and attainability condition, the following inequalities can be derived:

$$w(e,\hat{\theta},t) - \left(\hat{\theta}(t) - \theta\right)^T \nabla_{\hat{\theta}} w(e,\hat{\theta},t) \le w(e,\theta,t) \le -\rho(Q). \quad (27)$$

The time derivative of V_t along a trajectory of the system is given by

$$\begin{aligned} \dot{V}_t &= \dot{Q}_t + \left(\hat{\theta}(t) - \theta + \psi(e,\hat{\theta},t)\right)^T \Gamma^{-1}\left(\dot{\hat{\theta}} + \dot{\psi}(e,\hat{\theta},t)\right) \\ &= \dot{Q}_t + \left(\hat{\theta}(t) - \theta + \psi(e,\hat{\theta},t)\right)^T \Gamma^{-1} \cdot \\ &\quad \left(-\dot{\psi}(e,\hat{\theta},t) - \Gamma \nabla_{\hat{\theta}} w(e,\hat{\theta},t) + \dot{\psi}(e,\hat{\theta},t)\right) \\ &= \dot{Q}_t - \left(\hat{\theta}(t) - \theta\right)^T \nabla_{\hat{\theta}} w(e,\hat{\theta},t) - \psi(e,\hat{\theta},t)^T \nabla_{\hat{\theta}} w(e,\hat{\theta},t). \end{aligned} \quad (28)$$

From the pseudo gradientity condition $\psi^T \nabla_{\hat{\theta}} w \ge 0$,

$$\begin{aligned} \dot{V}_t &\le \dot{Q}_t - \left(\hat{\theta}(t) - \theta\right)^T \nabla_{\hat{\theta}} w(e,\hat{\theta},t) \\ &= w(e,\hat{\theta},t) - \left(\hat{\theta}(t) - \theta\right)^T \nabla_{\hat{\theta}} w(e,\hat{\theta},t). \end{aligned} \quad (29)$$

From (25), (27), $\dot{V}_t$ can be expressed as

$$\dot{V}_t \le w(e,\theta,t) \le -\rho(Q) < 0. \quad (30)$$

Therefore $Q_t \to 0$ as $t \to \infty$.

Q.E.D.

Corollary 1 : For (4), let the aim function Q_t :

$$Q_t = \frac{1}{2} e^T P e, \quad (31)$$

i.e.,

$$w = \frac{1}{2} e^T (A^T P + PA) e + e^T PB \tilde{\theta}^T \phi, \quad (32)$$

where $P \in R^{n \times n}$ is the solution to (13), and $\psi_i(e,\hat{\theta},t)$ in $\psi(e,\hat{\theta},t)$ of (24):

$$\psi_i(e,\hat{\theta},t) = e^T PB \phi_i(x), \quad i = 1, \cdots, r, \quad (33)$$

i.e., the update law :

$$\hat{\theta}_i = -e^T PB \phi_i(x) - \Gamma_i \int_0^t e^T(s) PB \phi_i(x(s)) ds, i = 1, \cdots, r, \quad (34)$$

where Γ_i are diagonal elements of the matrix $\Gamma = \gamma I_r$, where $\gamma > 0$ are a positive constant. Then all solutions of system (4), (24) are bounded and $Q_t \to 0$ as $t \to \infty$.

Proof : From (32), we can see that $w(e,\hat{\theta},t)$ is linear terms of $\hat{\theta}$ and that $w(e,\hat{\theta},t)$ is convex function in $\hat{\theta}$. From (13) and (32), $w(e,\hat{\theta},t)$ also holds the attainability condition if $\hat{\theta} = \theta$, i.e.,

$$w(e,\theta,t) = \frac{1}{2} e^T (A^T P + PA) e \le -\rho(Q), \quad (35)$$

and $\psi(e,\hat{\theta},t)$ in (33) satisfies pseudo gradient condition since $\nabla_{\hat{\theta}} w(e,\hat{\theta},t) = (e^T PB)\phi(x)$. Because (4), (32) and (33) hold the conditions of Theorem 2, the proof is similar to Theorem 2. Q.E.D.

IV. A Case Study

To demonstrate the validity of the proposed scheme, numerical studies are undertaken in this section. In order to compare the proposed method with Huang's method, we consider the same system, a mass-spring-damper system with friction, as in [8]. The dynamics of such a system can be written as

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= u - \theta_1 sgn(x_2) - \theta_2 x_1 - \theta_3 x_2 \end{aligned} \quad (36)$$

where x_1 is the position, x_2 is the velocity, θ_1 is the Coulomb force, θ_2 is the spring coefficient, and θ_3 is the damping coefficient. The corresponding basis functions are: $\phi(x) = [sgn(x_2)\, x_1\, x_2]^T$. The system and control parameters used in this simulation are: $\theta = [0.3\,0.1\,0.3]^T$, $k = [10.0\,5.0]^T$. In (4) and (13),

$$A = \begin{bmatrix} 0 & 1 \\ -10 & -5 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad P = \begin{bmatrix} 1.35 & 0.05 \\ 0.05 & 0.11 \end{bmatrix}.$$

The position of the mass is commanded to follow the trajectory: $x_1^d = \cos(t)$. The initial values are given as $x(0) = [0.5, 0.0]^T$, $\hat{\theta}(0) = [0\,0\,0]^T$.

In simulation of the uncompensated case, the control input is $u(t) = \dot{x}_n^d - k^T e$, i.e., the damping and the spring restoring forces are considered as unknown external disturbances.

In simulation of Huang's method [8], $\hat{\theta_1} = z_1 - |x_2(t)|$, $\hat{\theta_2} = z_2 - x_1 x_2(t)$, $\hat{\theta_3} = z_3 - (1/2)x_2^2(t)$, and

$$\dot{z}_1 = sgn(x_2)(u - \hat{\theta}^T\phi) - e^T PBsgn(x_2)$$
$$\dot{z}_2 = x_1(u - \hat{\theta}^T\phi) + x_2^2 - e^T PBx_1$$
$$\dot{z}_3 = x_2(u - \hat{\theta}^T\phi) - e^T PBx_2,$$

with the control input (3). In simulation of the proposed method,

$$\hat{\theta}_i = -e^T PB\phi_i(x) - \Gamma_i \int_0^t e^T(s) PB\phi_i(x(s))ds, \quad i = 1,2,3,$$

with the control input (3), where $\Gamma_i = 120, i = 1,2,3$. In simulation, the above integration is carried out based on the numerical integration from the initial time t_0 to t with sampling time $1msec$.

The trajectories of the tracking errors corresponding to these two designs appear in Fig. 1 and Fig. 2. It is observed that even though the proposed method shows a larger error than that of Huang's method in transient time, the steady state error is improved after 1.5 seconds. The large position or velocity error in consequence of the parameter error may be reduced by choosing the initial estimates to be closing values to real parameters. The parametric estimation results for Huang's method and the proposed design are given in Fig. 3 and Fig. 4, respectively.

Even though the estimation errors of the proposed method are larger than that of Huang's method within initial time interval, all three parameters are fast identified than that of Huang's method. In the proposed method, however, even though the state errors converge to zero, very small parameter estimation errors exist in the steady state after about 2 seconds. The reason is due to the fact that the speed gradient algorithm is originally designed such that the Lyapunov candidate function is not a Lyapunov function with respect to the parameter estimation error vector even though it is a Lyapunov function with respect to state error vector. From all simulation results, however, the result of the proposed method does not differ from one of Huang's method in the steady state. That is, the estimates of the parameter uncertainties converge to their true values because the sufficient rich conditions are satisfied.

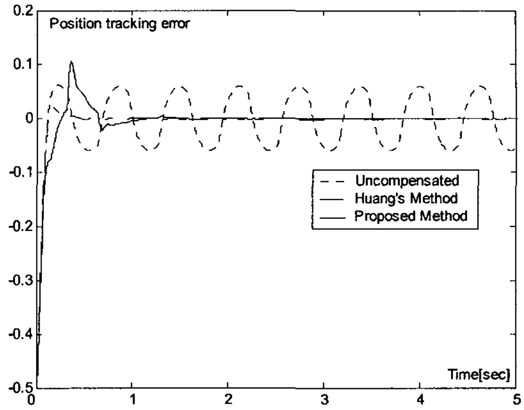

Fig. 1. Position tracking errors to the uncompensated, Huang's and the proposed method

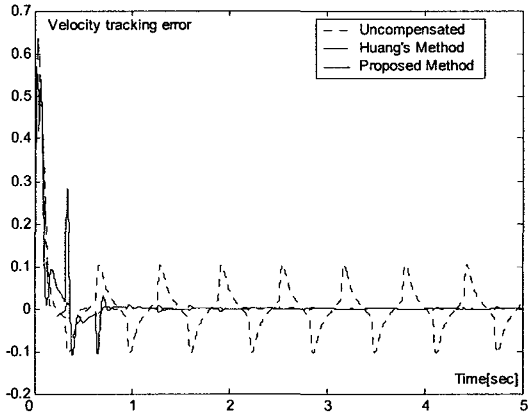

Fig. 2. Velocity tracking errors to the uncompensated, Huang's and the proposed method

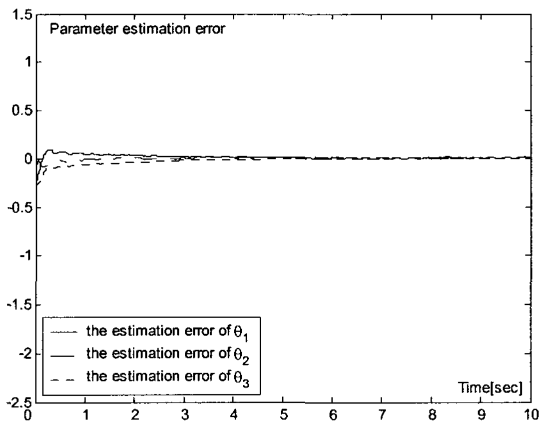

Fig. 3. Parameter estimation errors for Huang's method

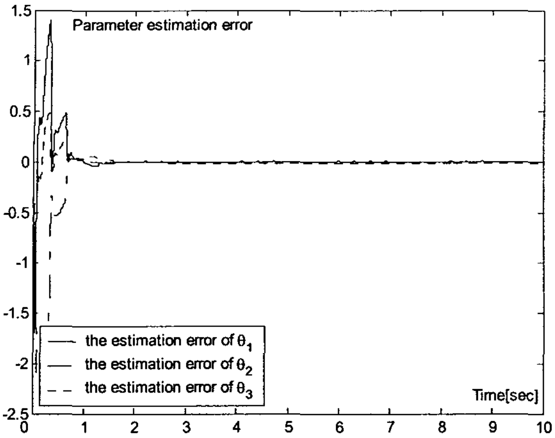

Fig. 4. Parameter estimation errors for the proposed design

II. Conclusions

An integration type adaptive compensation design for a class of linearly parameterized dynamical systems is presented. The proposed estimator need not the intermediate nonlinear function that has to guarantee some condition and affects the transient response of the estimator in prior suggested strategies. The proposed compensation scheme can be implemented by only selecting the design functions in parameter update law to be guaranteed growth, convexity, attainability and pseudo gradient conditions. The asymptotic stability of the tracking error and the boundedness of the estimation errors can be achieved based on SG algorithm. Through the simulations and comparison with [8], the validity of the proposed scheme is shown.

References

[1] B. Friedland and Y. Park, "On adaptive friction compensation," *IEEE Trans. Automat. Contr.*, vol. 37, pp. 1609-1612, Oct. 1992.

[2] B. Friedland, "A simple nonlinear observer for estimating parameters in dynamic systems," *in Proc. IFAC World Congr.*, Sydney, Australia, vol. 5, pp. 227-230, 1993.

[3] A. Yazdizadeh and K. Khorasani, "Adaptive friction compensation based on the Lyapunov scheme," *in Proc. IEEE Int. Conf. Contr. Applicat.*, Dearborn, MI, pp. 1060-1065, Sept, 1996.

[4] E. W. Bai, "Parametrization and adaptive compensation of friction forces," *Int. J. Adaptive Contr. Signal Processing*, vol. 11, pp. 21-31, 1997.

[5] T.-L. Liao and T.-I. Chien, "An exponentially stable adaptive friction compensator." *IEEE Trans. Automat. Contr.*, vol. 45, no. 5, pp. 977-980, May 2000.

[6] G. Song, L. Cai, Y. Wang, and R. W. Longman, "A sliding-mode based smooth adaptive robust controller for friction compensation," *Int. J. Robust Nonlinear Contr.*, vol. 8, pp. 725-739, 1998.

[7] B. Armstrong-Helouvry, P. Dupont, and C. Canudas deWit, "A survey of models, analysis tools and compensation methods for the control of machines with friction," *Automatica*, vol. 30, no. 7, pp. 1083-1138, 1994.

[8] J.-T. Huang, "An adaptive compensator for a class of linearly parameterized systems," *IEEE Trans. Automat. Contr.*, vol. 47, no. 3, pp. 483-486, Mar. 2002.

[9] S. W. Lee and J. H. Kim, "Robust adaptive stick-slip friction compensation," *IEEE Trans. Indust. Electroni.*, vol. 42, no. 5, pp. 474-479, 1995.

[10] C. Canudas de Wit, H. Olsson, K. J. Astrom, and P. Lischinsky, "A new model for control of systems with friction," *IEEE Trans. Automat. Contr.*, vol. 40, pp. 419-425, Mar. 1995.

[11] P. A. Ioannou and J. Sun, *Robust Adaptive Control*, Englewood Cliffs, NJ: Prentice-Hall, 1996.

[12] A. L. Fradkov, *Large-Scale Control Systems*, Leningrad, 1990.

[13] W. C. Ham and J. J. Lee, "Adaptive control based on speed gradient algorithm for robot manipulators," *IECON'94*, pp. 776-781, 1994.

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