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Robust Trajectory Control of Robot Manipulators Using Time Delay Control with Adaptive Compensator

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Abstract: An enhanced controller to improve the robustness of Time Delay Control (TDC) for a robot manipulator in the presence of hard nonlinearities is proposed. The problem of TDC is first analyzed with TDC as a trajectory control for a robot manipulator in the presence of hard nonlinearity. The method of steepest descent, which is a type of adaptive control scheme, is used to solve this problem in order to develop an enhanced controller. The proposed controller is called TDC with Adaptive Compensator (TDCAC). The adaptive compensator of TDCAC serves as a type of high pass filter for the effect of hard nonlinearities and is very intuitional for choosing the adaptive gain of the adaptive compensator. The robustness of TDCAC is verified by experiment.

1. INTRODUCTION

Time Delay Control (TDC) is the control technique which compensates for unpredicted disturbances of a plant and/or unknown dynamics of a plant with *Time Delay Estimation* (TDE) (Morgan *et al.*, 1985; Youcef-Toumi *et al.*, 1990; Hsia *et al.*, 1990). TDC has a distinct robustness for disturbances and parameter variations, although TDC has simpler structure than other advanced control algorithms developed until now, such as H^{∞} control and adaptive control. The effectiveness of TDC has been demonstrated by many successful applications in robotics (Hsia *et al.*, 1990; Chang *et al.*, 1996; Jung and Hsia *et al.*, 2004) and actuators (Chang *et al.*, 1999; Lee *et al.*, 2004). A robust control scheme similar to TDC is recently developed for only uncertain LTI systems (Zhong *et al.*, 2004).

In the presence of *hard nonlinearity*, such as coulomb friction/static friction, TDC shows problems commonly found in methods of PID control or disturbance observer (Chang and Park, 2001). Tracking error increases at zero velocity in systems having coulomb friction. Slow motions often involve stick-slip phenomena expressed in the form of limit cycle in the position control and oscillation in trajectory tracking control in the system having static friction and stribeck effect.

There are a few studies which strive to solve this problem. TDCSA, which is TDC with a compensator of the switching action based on Sliding Mode Control (SMC), was proposed by Chang and Park (2001). A control scheme which has the same structure as TDCSA was developed by Park and Kim (1999). The perturbation observer as a compensator for the problem of TDC was suggested by Nam (2005). TDCIM, which is TDC with an additional feedback loop based on Internal Model Control (IMC), was recently proposed to solve the problem of TDC (Cho and Chang *et al.*, 2005). A control scheme for impedance control was developed by Jin and Chang (2006), which uses both TDC and ideal velocity feedback loop to be more robust than TDC.

An enhanced controller to improve the robustness of Time Delay Control (TDC) for a robot manipulator in the presence of hard nonlinearities by using a kind of adaptive control scheme is proposed in this paper. Adaptive control is a control scheme which has a function to estimate uncertain plant parameters (or, equivalently, the corresponding controller parameters) on-line based on measured system signals, and uses the estimated parameters in the control input computation to remedy situations with parameter uncertainty (Slotine and Li, 1991). The problem of TDC in the presence of hard nonlinearity has been remedied by the adaptive law of a proposed controller, since the effect of hard nonlinearity is estimated and compensated by an adaptive law. We have investigated the properties and performances of a proposed controller.

This paper is outlined as follows. In Section II, the TDC are briefly reviewed and its problem is analyzed. An enhanced controller named TDCAC is proposed and its some properties are analyzed in Section III. The robustness of TDCAC is verified through 1 degree-of-freedom (D-O-F) experiment in Section IV. At last, concluding remarks are given in Section V.

2. PROBLEMS OF TDC DUE TO THE TDE ERROR

We summarize the TDC law for robot manipulators (Hsia *et al.*, 1990) and analyze its problems concerning TDE error (Chang and Park, 2001; Lee and Chang, 2002; Jin and Chang, 2006).

2.1 Review of the TDC

The dynamics of n DOF robot manipulators is generally described as follows:

$$\mathbf{M}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \mathbf{V}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) + \mathbf{G}(\boldsymbol{\theta}) + \mathbf{F}(\dot{\boldsymbol{\theta}}) + \mathbf{w} = \boldsymbol{\tau} \qquad (1)$$

where $\boldsymbol{\theta},\dot{\boldsymbol{\theta}},\ddot{\boldsymbol{\theta}} \in \Re^n$ denote the joint angle, joint angular velocity, and joint angular acceleration, respectively; $\mathbf{M}(\boldsymbol{\theta}) \in \Re^{n\times n}$ the inertia matrix; $\mathbf{V}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) \in \Re^n$ the Coriolis and the centrifugal forces; $\mathbf{G}(\boldsymbol{\theta}) \in \Re^n$ terms due to gravity; $\mathbf{F}(\dot{\boldsymbol{\theta}}) \in \Re^n$ friction; $\mathbf{w} \in \Re^n$ the unmodeled dynamics or disturbances; and $\boldsymbol{\tau} \in \Re^n$ denotes the input torque. By introducing a constant diagonal matrix, $\bar{\mathbf{M}} \in \Re^{n\times n}$, which represents the known part of $\mathbf{M}(\boldsymbol{\theta})$, one can rewrite (1) as follows:

$$\bar{\mathbf{M}}\ddot{\boldsymbol{\theta}} + \mathbf{H}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}},\ddot{\boldsymbol{\theta}}) = \boldsymbol{\tau}, \qquad (2)$$

where $\mathbf{H}\left(\boldsymbol{\theta},\dot{\boldsymbol{\theta}},\ddot{\boldsymbol{\theta}}\right)$ denotes the total sum of the nonlinear dynamics of robot manipulators, frictions, and disturbances, and is described as follows:

$$\mathbf{H}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}},\ddot{\boldsymbol{\theta}}) = (\mathbf{M}(\boldsymbol{\theta}) - \bar{\mathbf{M}})\ddot{\boldsymbol{\theta}} + \mathbf{V}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) + \mathbf{G}(\boldsymbol{\theta}) + \mathbf{F}(\dot{\boldsymbol{\theta}}) + \mathbf{w} \;.(3)$$

The control objective of TDC, like the computed torque method, is to achieve the following error dynamics:

$$\ddot{\mathbf{e}} + \mathbf{K}_D\dot{\mathbf{e}} + \mathbf{K}_P\mathbf{e} = \mathbf{0}, \qquad (4)$$

where $\mathbf{e} \triangleq \boldsymbol{\theta}_d - \boldsymbol{\theta}$. To this end, the control torque τ is designed based on the computed torque control as follows:

$$\boldsymbol{\tau} = \bar{\mathbf{M}}\mathbf{u} + \hat{\mathbf{H}}\text{ , and} \qquad (5)$$

$$\mathbf{u} = \ddot{\boldsymbol{\theta}}_d + \mathbf{K}_D\left(\dot{\boldsymbol{\theta}}_d - \dot{\boldsymbol{\theta}}\right) + \mathbf{K}_P\left(\boldsymbol{\theta}_d - \boldsymbol{\theta}\right), \qquad (6)$$

where $\hat{\mathbf{H}}$ denotes the *estimated* value of $\mathbf{H}$; $\boldsymbol{\theta}_d,\dot{\boldsymbol{\theta}}_d,\ddot{\boldsymbol{\theta}}_d \in \Re^n$ denote the desired trajectory and its time derivatives, respectively; and $\mathbf{K}_D \in \Re^{n\times n}$, $\mathbf{K}_P \in \Re^{n\times n}$ represent the *diagonal* gain matrices of decoupled PD controllers. In essence, therefore, the control (5) attempts to *cancel* $\mathbf{H}$ in (2) by $\hat{\mathbf{H}}$ and inject a desired dynamics in (6).

Whereas the computed torque method incorporates real-time computation of $\hat{\mathbf{H}}$ based on a robot dynamic model, TDC uses the *time delay estimation* (TDE) described as follows: Under the assumption that $\mathbf{H}$ is continuous or piecewise continuous and the time delay L is sufficiently small, the following approximation holds:

$$\mathbf{H}_{(t)} \cong \mathbf{H}_{(t-L)}, \qquad (7)$$

providing an excellent estimation of $\mathbf{H}_{(t)}$, i.e.

$$\hat{\mathbf{H}}_{(t)} \triangleq \mathbf{H}_{(t-L)}, \qquad (8)$$

which is the essential idea of the TDC. The TDE can be derived from (2) as follows:

$$\hat{\mathbf{H}}_{(t)} = \mathbf{H}_{(t-L)} = \boldsymbol{\tau}_{(t-L)} - \bar{\mathbf{M}}\ddot{\boldsymbol{\theta}}_{(t-L)} \,. \qquad (9)$$

Note that (9) is a *causal* relationship. Using the TDE for $\hat{\mathbf{H}}$ in (9) leads (5) to

$$\boldsymbol{\tau}_{(t)} = \boldsymbol{\tau}_{(t-L)} - \bar{\mathbf{M}}\ddot{\boldsymbol{\theta}}_{(t-L)} + \bar{\mathbf{M}}\mathbf{u}_{(t)} \,. \qquad (10)$$

The final form of TDC results from (2) and (6) like this:

$$\begin{aligned}\boldsymbol{\tau} = {} & \boldsymbol{\tau}_{(t-L)} - \bar{\mathbf{M}}\ddot{\boldsymbol{\theta}}_{(t-L)} \\ & + \bar{\mathbf{M}}\left[\ddot{\boldsymbol{\theta}}_{d(t)} + \mathbf{K}_D\left(\dot{\boldsymbol{\theta}}_{d(t)} - \dot{\boldsymbol{\theta}}_{(t)}\right) + \mathbf{K}_P\left(\boldsymbol{\theta}_{d(t)} - \boldsymbol{\theta}_{(t)}\right)\right]\end{aligned} . \qquad (11)$$

Owing to the TDE, the TDC has a simple structure and is very efficient – approximately as efficient as a typical PID control. Furthermore, since $\bar{\mathbf{M}}$ is selected as a diagonal matrix, the TDC can be designed for *n individual* joint controllers by using each diagonal element of $\bar{\mathbf{M}}$, that of $\mathbf{K}_D$, and that of $\mathbf{K}_P$. Fig. 1 shows the block diagram of the closed-loop system due to the TDC. Notice that the TDC may be viewed as consisting of three functions: (A) feed-forward function processing $\boldsymbol{\theta}_d$; (B) feedback linearization using the TDE; and (C) the PD-type feedback of $\boldsymbol{\theta}$.

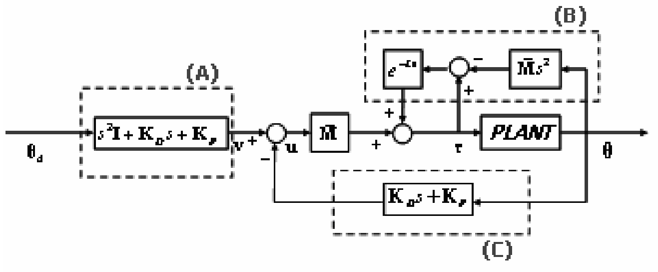

Fig. 1. Block diagram of TDC

2.2 Problems of the TDC concerned with the TDE error

If the time delay L is set infinitesimally small, a perfect estimation of $\mathbf{H}$ would be possible by using the TDE. Because of digital implementation, however, the smallest value for the time delay L is the sampling time, which is finite. Therefore, the estimation error results from a finite L. The following relationship is derived from substituting (5) into (2) and considering (8):

$$\mathbf{H}_{(t)} - \hat{\mathbf{H}}_{(t)} = \mathbf{H}_{(t)} - \mathbf{H}_{(t-L)} = \bar{\mathbf{M}}\left(\mathbf{u}_{(t)} - \ddot{\boldsymbol{\theta}}_{(t)}\right). \qquad (12)$$

The LHS of the above equation denotes the estimation error. Now define the *TDE error*, $\boldsymbol{\varepsilon}_{(t)}$ as follows:

$$\boldsymbol{\varepsilon}_{(t)} \triangleq \bar{\mathbf{M}}^{-1}\left(\mathbf{H}_{(t)} - \mathbf{H}_{(t\text{-}L)}\right) = \mathbf{u}_{(t)} - \ddot{\boldsymbol{\theta}}_{(t)} \qquad (13)$$

Substituting (6) into(13), we obtain the error dynamics of the TDC:

$$\ddot{\mathbf{e}}_{(t)} + \mathbf{K}_D\dot{\mathbf{e}}_{(t)} + \mathbf{K}_P\mathbf{e}_{(t)} = \boldsymbol{\varepsilon}_{(t)}, \qquad (14)$$

which clearly shows the influence of the TDE error, $\boldsymbol{\varepsilon}_{(t)}$, on the tracking error, $\mathbf{e}_{(t)}$.

Especially, under *hard nonlinearities*, such as Coulomb friction and static friction, $\mathbf{F}(\dot{\boldsymbol{\theta}})$ of (3) becomes discontinuous and then the continuity assumption of $\mathbf{H}_{(t)}$ in (7) is invalid. As a result, a large *TDE error* is occurred in (9) under hard nonlinearities. *A large TDE error results in a large tracking error as* (14).

3. PROPOSITION: TIME DELAY CONTROL WITH ADAPTIVE COMPENSATOR

An enhanced controller, which has a function to compensate for TDE error, is proposed. *The method of steepest descent*, which is a type of adaptive control scheme, was used to design a new controller. The new controller is called *Time Delay Control with Adaptive Compensator* (TDCAC). Stability issues and its properties are also analyzed.

3.1 Derivation of TDCAC

The control law of TDCAC is designed as follows:

$$\begin{aligned}\boldsymbol{\tau} &= \boldsymbol{\tau}_{(t-L)} - \bar{\mathbf{M}}\ddot{\boldsymbol{\theta}}_{(t-L)} \\ &+ \bar{\mathbf{M}}(\ddot{\boldsymbol{\theta}}_d + \mathbf{K}_D(\dot{\boldsymbol{\theta}}_d - \dot{\boldsymbol{\theta}}) + \mathbf{K}_P(\boldsymbol{\theta}_d - \boldsymbol{\theta})) + \bar{\mathbf{M}}\hat{\boldsymbol{\varepsilon}}_{(t)}\end{aligned}, \quad (15)$$

where $\hat{\boldsymbol{\varepsilon}}$, which serves as an adaptive compensator, compensates for TDE error.

Closed-loop error dynamics derived from (15) and (2) is as follows:

$$\ddot{\mathbf{e}}_{(t)} + \mathbf{K}_D\dot{\mathbf{e}}_{(t)} + \mathbf{K}_P\mathbf{e}_{(t)} = \boldsymbol{\varepsilon}_{(t)} - \hat{\boldsymbol{\varepsilon}}_{(t)} = -\tilde{\boldsymbol{\varepsilon}}_{(t)}, \quad (16)$$

where $\tilde{\boldsymbol{\varepsilon}}_{(t)} \triangleq \hat{\boldsymbol{\varepsilon}}_{(t)} - \boldsymbol{\varepsilon}_{(t)}$ denotes the estimation error of TDE error.

An adaptive compensator was designed by *the method of steepest descent* using a cost function of the estimation error. A cost function for design was made as follows:

$$\mathbf{J}\left(\tilde{\boldsymbol{\varepsilon}}_{(t)}\right) = \frac{1}{2}\tilde{\boldsymbol{\varepsilon}}_{(t)}^{\mathbf{T}}\tilde{\boldsymbol{\varepsilon}}_{(t)}. \quad (17)$$

If TDE error was slow-varying or constant, an adaptive compensator was designed by the method of steepest descent as follows:

$$\dot{\hat{\boldsymbol{\varepsilon}}}_{(t)} = -\boldsymbol{\gamma}\frac{\partial[\mathbf{J}]}{\partial\hat{\boldsymbol{\varepsilon}}} = -\boldsymbol{\gamma}\left[\tilde{\boldsymbol{\varepsilon}}_{(t)}\right] = \boldsymbol{\gamma}\left[\ddot{\mathbf{e}}_{(t)} + \mathbf{K}_D\dot{\mathbf{e}}_{(t)} + \mathbf{K}_P\mathbf{e}_{(t)}\right], \quad (18)$$

where $\boldsymbol{\gamma} \triangleq \mathrm{diag}(\gamma_1,\ldots,\gamma_n)$ denotes an adaptive gain matrix of which elements are always positive.

The term $\hat{\boldsymbol{\varepsilon}}_{(t)}$ in (18), an adaptive compensator, is updated to the direction of decreasing TDE error, because the method of steepest descent always makes the slope of cost function be negative.

The overall control law of TDCAC is as follows:

$$\begin{aligned}\boldsymbol{\tau}_{(t)} &= \boldsymbol{\tau}_{(t-L)} - \bar{\mathbf{M}}\ddot{\boldsymbol{\theta}}_{(t-L)} \\ &+ \bar{\mathbf{M}}\left(\ddot{\boldsymbol{\theta}}_d + \mathbf{K}_D\left(\dot{\boldsymbol{\theta}}_d - \dot{\boldsymbol{\theta}}\right) + \mathbf{K}_P\left(\boldsymbol{\theta}_\mathbf{d} - \boldsymbol{\theta}\right)\right) + \bar{\mathbf{M}}\hat{\boldsymbol{\varepsilon}}_{(t)} \\ \dot{\hat{\boldsymbol{\varepsilon}}}_{(t)} &= -\boldsymbol{\gamma}\tilde{\boldsymbol{\varepsilon}} = \boldsymbol{\gamma}\left[\ddot{\mathbf{e}}_{(t)} + \mathbf{K}_D\dot{\mathbf{e}}_{(t)} + \mathbf{K}_P\mathbf{e}_{(t)}\right]\end{aligned}. \quad (19)$$

The block diagram of TDCAC is shown in Fig. 2. TDCAC only consists of an adaptive compensator and an original TDC for a robot manipulator (Hsia *et al.*, 1990).

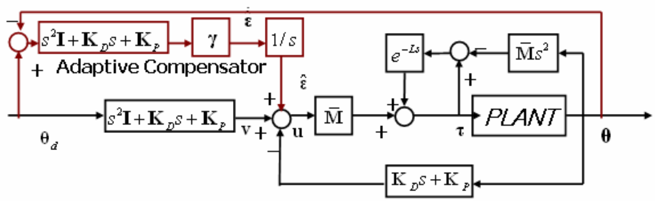

Fig. 2. Block diagram of TDCAC

3.2 Stability analysis of TDCAC

Theorem 1. [Stability of TDCAC]

If the TDCAC law of (19) is used, and both $\bar{\mathbf{M}} \triangleq \mathrm{diag}(\alpha_1,\ldots\alpha_n)$ and $\boldsymbol{\gamma} \triangleq \mathrm{diag}(\gamma_1,\ldots,\gamma_n)$ are chosen such that

$$\alpha_i < \frac{2+L\gamma_i}{1+L\gamma_i}\rho, \quad (20)$$

where L sampling time; ρ the minimum value of $\lambda(\mathbf{M}^{-1})$, then closed-loop system becomes stable for a sufficiently small L.

Proof: The proof in (Hsia *et al.*, 1990; Jung and Chang *et al.*, 2004) can be immediately applied to this case with few modifications, because there are few differences in the assumptions and conditions. (Q.E.D.)

3.3 Properties of TDCAC

1) Property of adaptive compensator as high-pass filter

An adaptive compensator can be characterized as a type of a high-pass filter for TDE error (Fig. 3). This is certain reason why TDCAC is more robust against TDE error than TDC. Assume that 1 D-O-F robot manipulator is used to analyze this property of adaptive compensator for simplicity.

From using the time derivative of TDE error, an adaptive compensator (18) is re-written:

$$\dot{\tilde{\varepsilon}}_{(t)} = \dot{\hat{\varepsilon}}_{(t)} - \dot{\varepsilon}_{(t)} = -\gamma\tilde{\varepsilon}_{(t)} - \dot{\varepsilon}_{(t)}, \quad (21)$$

where the output of a high-pass filter is the estimated error of TDE error, $\tilde{\varepsilon}_{(t)}$, the input of a high-pass filter is TDE error, $\varepsilon_{(t)}$ and the cut-off frequency of a high-pass filter is a adaptive gain, γ. The frequency response function of a filter is derived from (21) as follows:

$$\mathbf{G}(jw) = \frac{\tilde{\varepsilon}(s)}{\varepsilon(s)} = \frac{-jw(1/\gamma)}{1+jw(1/\gamma)}$$
$$\left|\mathbf{G}(jw)\right| = \frac{w(1/\gamma)}{\sqrt{1+\left(w(1/\gamma)\right)^2}} \quad (22)$$

The frequency magnitude plot of (22) is shown in Fig. 4. The larger the adaptive gain, the more robust it is against a low frequency part of TDE error (Fig. 4).

The power spectrum of the input/output of an adaptive compensator in the simulation using 1 D-O-F manipulator (Fig. 5) with Coulomb friction model, one of hard nonlinearities (Fig. 6) is shown in Fig. 7. The γ of TDCAC in simulation is also shown in Fig. 7. Notice that other conditions of this simulation are explained in Cho *et al.*, 2005. The low frequency part of TDE error is compensated for by an adaptive compensator, since an adaptive compensator functions as a high-pass filter.

Fig. 3. Adaptive Compensator as high-pass filter

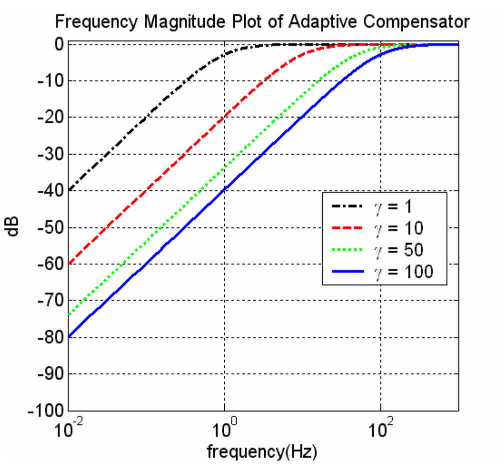

Fig. 4. Frequency magnitude plot of Adaptive Compensator

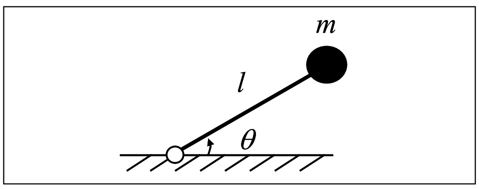

Fig. 5. 1 DOF link system. $l = 1.0(m)$ and $m = 1.0(kg)$

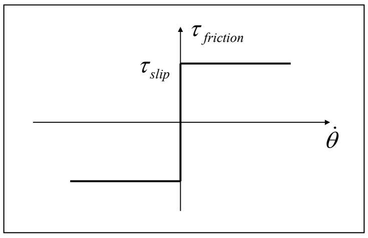

Fig. 6. Coulomb friction model: τ_{slip} denotes the Coulomb friction coefficient

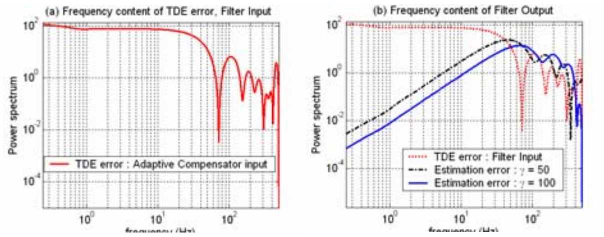

Fig. 7. Frequency Contents of Filter Input/Output

2) Simple gain tuning procedure of adaptive gains

There are two gain matrices, such as $\bar{\mathbf{M}} = \mathrm{diag}(\alpha_1,\ldots,\alpha_n)$ and $\boldsymbol{\gamma} \triangleq \mathrm{diag}(\gamma_1,\ldots\gamma_n)$, in the control law of TDCAC. Notice that $\mathbf{K}_D, \mathbf{K}_P$ is automatically resulted from the desired error dynamics. The gain tuning procedure of TDCAC is as follows:

First, α_i has to be determined as TDC case. Next, γ_i has to be determined. An advantage of TDCAC is that the choice of γ_i is very intuitional, because the adaptive gain of the adaptive compensator, γ_i is the same as the cut-off frequency of the high-pass filter. The enhancement of performance is expected as increasing in adaptive gain, because a low frequency part of TDE error is more cancelled out with increase in the cut-off frequency of the adaptive compensator (Fig. 4, 5). Therefore, an adaptive gain can be chosen as the biggest value in the condition of satisfying the stability condition of TDCAC (20).

The variation of trajectory tracking error according to the change of adaptive gain is demonstrated by numerical experiment. The closed-loop error dynamics of TDCAC (16) in the case of 1 D-O-F manipulator is re-written as follows:

$$\ddot{e}_{(t)} + (K_D + \gamma)\dot{e}_{(t)} + (K_P + \gamma K_D)e_{(t)} + \gamma K_P \int e(\tau)d\tau = \bar{M}^{-1}\Delta H(t) \quad (23)$$

The result of simulation using (23) is shown in Fig. 8, provided that the TDE error is:

$$\Delta H = 1.0\delta(t-1). \quad (24)$$

Three adaptive gains, such as 10, 50 and 100, of the adaptive compensator are used to perform the simulation.

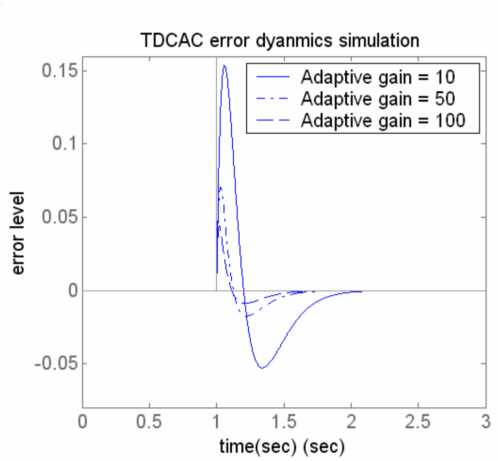

Fig. 8. Simulation – TDCAC error dynamics

The enhancement of performance is shown as increasing in adaptive gain (Fig. 8).

4. EXPERIMENTAL VERIFICATION

In this section, the performance of TDCAC is compared with that of TDC through experiments with 1 DOF linear motor (Fig. 9), in order to confirm the robustness of TDCAC.

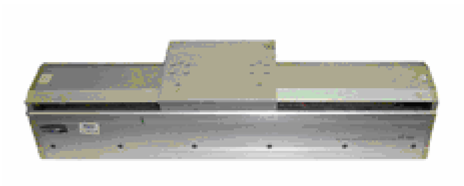

Fig. 9. Linear Motor (JTM 10)

4.1 Linear Motor System

The reduced mathematical model of linear motor system is as follows:

$$\frac{MR_i}{K_T}\frac{d^2x}{dt^2} + K_E\frac{dx}{dt} + \frac{R_i}{K_T}F_f = u, \qquad (25)$$

where x denotes the position of motor; u the input voltage; $M = 3kg$ the mover mass of motor; $K_T = 16N/A$ the force constant; F_f the friction force; $R_i = 15.2\Omega$ the electrical resistance; $K_E = 16V\cdot\sec/m$ means the back-EMF constant.

4.2 Experimental Set up

TDC is designed as follows:

$$u_{(t)} = u_{(t-L)} - \bar{M}\ddot{x}_{(t-L)} + \bar{M}\left(\ddot{x}_d + K_D\left(\dot{x}_d - \dot{x}\right) + K_P\left(x_d - x\right)\right) \quad (26)$$

TDCAC is designed as follows:

$$u_{(t)} = u_{(t-L)} - \bar{M}\ddot{x}_{(t-L)} + \bar{M}\left(\ddot{x}_d + K_D\left(\dot{x}_d - \dot{x}\right) + K_P\left(x_d - x\right)\right) + \bar{M}\hat{\varepsilon}_{(t)}$$
$$\dot{\hat{\varepsilon}}_{(t)} = \gamma\left(\left(\ddot{x}_d - \ddot{x}\right) + K_D\left(\dot{x}_d - \dot{x}\right) + K_P\left(x_d - x\right)\right) \qquad (27)$$

All gains of TDC and TDCAC are best tuned to minimize tracking error as shown in Table 1. Note that the PD gains of all controllers are $K_D = 20, K_P = 100$ in order for desired error dynamics to be critical-damped $\left(\varsigma = 1, \omega_n = 10\text{rad/s}\right)$. Both the sampling time and the time delay for TDE are set to L=0.001 sec.

Table 1. Control gains for experiments

TDC	$\bar{M} = 0.0003$
TDCAC	$\bar{M} = 0.0003$, $\gamma = 1.333$

4.3 Experiment results

The reference trajectory is:

$$x_{d(t)} = 10.0\left(1 - e^{-\omega_d t}\right)\sin\left(\omega_d t\right)(mm), \qquad (28)$$

where ω_n denotes the frequency of reference trajectory, 0.25Hz.

Experimental results are shown in Fig. 10 and Fig. 11. And maximum tracking errors are arranged in Table 2.

The plant controlled by TDC has large tracking error due to coulomb friction, one of hard nonlinearity, when the plant passes by zero velocity (Fig. 10 (a) and (b)). In TDCAC case, tracking error is reduced decently, and then it is confirmed that the adaptive compensator works well (Fig. 10 (e)).

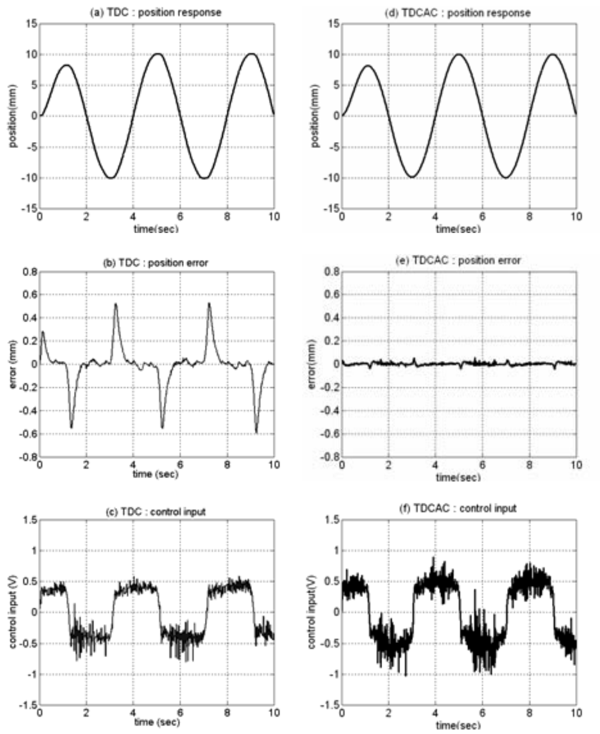

Fig. 10. Experimental results – TDC, TDCAC

Table 2. Max. error in Fig. 10

TDC	TDCAC
±0.60mm	±0.048mm

5. CONCLUSIONS

A new simple controller, called TDCAC, is proposed for the control of a robot manipulator in this paper. The performance of the controller is more robust than TDC, because TDE error is effectively cancelled out on-line by an adaptive compensator of TDCAC, which is based on the method of steepest descent. An adaptive compensator serves as a type of high pass filter for TDE error, while the choice of adaptive gain is intuitional. Experiments with a 1 D-O-F robot manipulator are occurred in order to verify the robustness of TDCAC. In the future, the experiment of TDCAC with a multi D-O-F robot manipulator should be carried out.

Acknowledgement

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