On the Controllers Based on Time Delay Estimation for Robotic Manipulators

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Abstract— **Assurance of asymptotic trajectory tracking in robotic manipulators with a smooth control law in the presence of unmodeled dynamics or external disturbance is a challenging problem. Recently, it is asserted that it is achieved via a rigorous proof by designing a traditional model-free controller together with time delay estimation (TDE) such that neither dynamical parameters nor conservative assumptions on external disturbance are required. The purpose of this note is to show that this claim is not true and the stability proof of the method is incorrect. Finally, some modified versions of this controller with rigorous proof is presented for robotic manipulators.**

Index terms— **Time delay estimation, robotic manipulators, proof of stability, uncertain system.**

I. INTRODUCTION

The performance of a robotic system is subject to some common challenges such as unmodeled dynamics, external disturbance, parameter uncertainties, etc. Several methods have been proposed to address these problems, and as a representative, adaptive controllers to address parametric uncertainties [1]–[5] and robust controllers to reject unmodeled dynamics/ external disturbance [6]–[9] could be listed. In adaptive control, it is usually assumed that the structure of the model is known, but the parameters are uncertain. Robust controllers can reject special types of disturbance, while some of them suffering from chattering in response. Under these assumptions and cumbersome calculations in some methods, asymptotic trajectory tracking is mathematically ensured.

Recently, it has been claimed that the design of a simple model-free controller with time delay estimation (TDE) makes it possible to guarantee trajectory tracking; see for example [10]–[15] and references therein. In this method, the robot's dynamic model is not required to be known in the controller synthesis, but instead, the dynamic behavior of the system in the previous time steps is used. By this means, a desired model with a constant inertia matrix is considered, and a simple controller synthesis without knowing the system dynamics is performed. Hereupon, it is claimed that trajectory tracking is ensured mathematically. For this purpose, it is asserted in their proof (see for example, Theorem 1 of [12]–[14] and section 5 of [15]) that the dynamic of TDE error is represented by a set of linear discrete-time equations with an Hurwitz matrix and thus, the TDE error has an upper bound. A claim which is totally questionable.

In this note, the stability of TDE-based controllers for robotic manipulators is investigated. It is shown that the upper bound of TDE error is limited only if the stability of the manipulator is ensured. Hence, the upper bound of the TDE error is state-dependent and it is not independent of the system's stability. Furthermore, the dynamic of TDE error is represented by a set of discrete-time linear time-varying equations and thus, its stability may not be achieved by merely Hurwitz condition [16, ch. 4]. Therefore, the stability of TDE-based controllers for robotic manipulators is doubtful.

II. TDE-BASED CONTROLLER SYNTHESIS FOR ROBOTIC MANIPULATORS

Here, the main concept of TDE-based controllers for robotic systems is proposed. Consider dynamical formulation of a n-DOF robot in the following form [13], [14], [17]

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + f(q,\dot{q}) + d = \tau, \qquad (1)$$

in which $q \in \mathbb{R}^n$ is joint position, $\dot{q} \in \mathbb{R}^n$ denotes velocity and $\ddot{q} \in \mathbb{R}^n$ is acceleration. $M(q) \in \mathbb{R}^{n \times n}$ and $C(q,\dot{q}) \in \mathbb{R}^{n \times n}$ are the positive definite inertia matrix, and the centrifugal and Coriolis matrix, respectively, $g(q) \in \mathbb{R}^n$ is the vector of gravity terms, $f(q,\dot{q}) \in \mathbb{R}^n$ denotes the system natural damping terms, and $d, \tau \in \mathbb{R}^n$ denotes the external disturbance and control input, respectively. Note that in some papers, e.g., [14], the dynamic of the actuators is also considered. However, for simplicity, it is not considered in this note. Dynamic model (1) is rewritten in the following form

$$\overline{M}\ddot{q} + h(q,\dot{q},\ddot{q}) = \tau, \qquad (2)$$

where $\overline{M} \in \mathbb{R}^{n \times n}$ is a constant matrix. The vector h that describes the remaining terms in the dynamic formulation is given by:

$$h(q,\dot{q},\ddot{q}) = (M - \overline{M})\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + f(q,\dot{q}) + d. \qquad (3)$$

The TDE–based control law is designed as follows

$$\tau = \overline{M}u + \hat{h}, \qquad (4)$$

in which u is the main controller that is chiefly different types of sliding mode controller and $\hat{h}$ is estimated value of h which is derived base on TDE method as follows

$$\hat{h}(t) \approx h(t - \rho) = \tau(t - \rho) - \overline{M}\ddot{q}(t - \rho), \qquad (5)$$

in which ρ denotes the time delay. The last term in (5) is usually unknown. Hence, the following numerical differentiation is used

$$\ddot{q}(t - \rho) \approx \big(q(t) - 2q(t - \rho) + q(t - 2\rho)\big)/\rho^2.$$

In order to ensure trajectory tracking in the relevant articles, first, it has been shown that the TDE error and its derivatives

are bounded, and then, the stability of the closed-loop system is guaranteed via the direct Lyapunov method. The critical part of the proof is to ensure the boundedness of $h - \hat{h}$ and its derivative. In the next section, this issue is analyzed in detail.

III. MAIN RESULTS

A. Analysis of TDE error

For the sake of simplicity, define

$$e = \overline{M}^{-1}(\hat{h} - h).$$

Using (1-5), the following equations are derived

$$
\begin{aligned}
Me &= M(\ddot{q} - u) = \tau - d - f - g - C\dot{q} - Mu \\
&= (\overline{M} - M)u + \hat{h} - \mathcal{N}(t) = (\overline{M} - M)u \\
&+ (M(t - \rho) - \overline{M})\ddot{q}(t - \rho) + \mathcal{N}(t - \rho) - \mathcal{N}(t), \quad (6)
\end{aligned}
$$

with

$$\mathcal{N}(t) = d(t) + f(t) + g(t) + C(t)\dot{q}(t).$$

Note that all the vectors and matrices are at time t unless indicated. Since $\ddot{q}(t - \rho) = e(t - \rho) + u(t - \rho)$, (6) is rewritten as follows

$$
\begin{aligned}
Me &= (M - \overline{M})e(t - \rho) - (M - \overline{M})(u - u(t - \rho)) \\
&+ (M(t - \rho) - M)\ddot{q}(t - \rho) + \mathcal{N}(t - \rho) - \mathcal{N}(t), \quad (7)
\end{aligned}
$$

where $\pm M\ddot{q}(t - \rho)$ was added to the last equation of (6). Therefore, the error e may be expressed in the following form

$$e(t) = De(t - \rho) + \xi \quad (8)$$

with

$$
\begin{aligned}
D &= I - M^{-1}(t)\overline{M} \\
\xi &= D(u - u(t - \rho)) + M^{-1}\Big((M(t - \rho) - M)\ddot{q}(t - \rho) \\
&+ \mathcal{N}(t - \rho) - \mathcal{N}(t)\Big). \quad (9)
\end{aligned}
$$

Equation (8) may be interpreted as a discrete system with input ξ. In the literature, it is asserted that bv suitable design of $\overline{M}$, the system (8) is bounded-input bounded-output and therefore, TDE error is bounded if ξ is bounded. Additionally, the upper bound of derivative of TDE error is given as:

$$
\begin{aligned}
\|\dot{e}\| &\approx \|\frac{e(t) - t(t - \rho)}{\rho}\| = \frac{1}{\rho}\| - M^{-1}\overline{M}e(t - \rho) + \xi\| \\
&\leq \frac{1}{\rho}(\|M^{-1}\|\|\overline{M}\|\|e(t - \rho)\| + \|\xi\|). \quad (10)
\end{aligned}
$$

Thus, the derivative of the TDE error is bounded if TDE error and $\|\xi\|$ are bounded. By considering (9), it is clear that ξ depends on the position, velocity, and acceleration. Thus, boundedness of ξ is only ensured if $q, \dot{q}$ and $\ddot{q}$ are bounded. This means that for the boundedness of the TDE error, stability of the system is required. It is a common technical error in TDE-based papers, in which the cause and effect are intertwined. Additionally, the matrix D given in

(9) ic not clearly constant. Hereupon, the system (8) is linear time-varying and its stability is not deduced from Hurwitz condition [16, ch. 4] and should be analyzed via other methods such as Lyapunov. Hence, according to these reasons, it is inferred that the stability of TDE-based controllers is not correct, and the proposed experiments/ simulations in the related articles are not confirmed by mathematical proof.

Remark 1: In some papers, such as [13], [14] the authors have tried to address this problem through another unrealistic assumption. They have presumed that the velocity and acceleration are bounded. Although in practical implementations this might be observed; however, this assumption is equivalent to assuming the stability of the closed-loop system. Furthermore, it is clear that an assumption should be defined such that it is verifiable at least in simulation, e.g., type of external disturbance, initial conditions, the precise values of states, etc. The boundedness of states and their derivatives should be assured by suitable control law and rigorous stability analysis. Therefore, this assumption does not rectify the problem while it is an obvious contradiction with the aim of the stability analysis.

Remark 2: As explained in section II, designing a TDE-based controller is based on a traditional controller together with a TDE-based component. Therefore, an extension of the method which could be applicable to a wide range of systems seems to be simple and is proposed as follows. As an example, consider interconnection and damping assignment passivity-based control (IDA-PBC) approach, which is a comprehensive method that stabilizes the general system $\dot{x} = f(x) + g(x)u$ at the equilibrium point x^* through solving a set of partial differential equations (PDEs) [6], [18]. It may seem that combining IDA-PBC with a TDE-based component, makes it possible to stabilize a system since the solutions of PDEs are selected freely and the remaining terms in the closed-loop dynamics resulted from the terms not satisfying the matching equations, could be considered as disturbance and rejected by TDE part. However, as explained before, the stability proof of TDE-based controllers is incorrect. Hence, the difficulty of solving a set of PDEs is the expense of precise stability assurance.

B. Overall stability analysis

Under the boundedness of TDE error, it is easy to ensure boundedness of the tracking error with a continuous control law, or asymptotic trajectory tracking with a non-continuous controller. However, in some of the papers that the main controller is based on higher order sliding mode such as [13], [14], [19], [20], it is argued that asymptotic stability is ensured via a continuous controller. Consider the case where the main controller is the super-twisting algorithm. It has been asserted that the closed-loop equations are expressed in the following form

$$
\begin{aligned}
\dot{s} &= -K_1\Lambda(s)\text{sign}(s) + \Omega \\
\dot{\Omega} &= -K_2\text{sign}(s) + \dot{e} \quad (11)
\end{aligned}
$$

with $\Lambda(s) = \text{diag}[|s_1|^{0.5}, ..., |s_n|^{0.5}]$ and s is sliding surface. Then by considering a Lyapunov function in the form $V = $

$\eta^T P \eta$ with $\eta = [\Lambda(s)\text{sign}(s)^T, \Omega^T]^T$, it has been shown that the derivative of the Lyapunov function is in the form $-\eta^T Q \eta$ such that by suitable values of K_1 and K_2, the matrix Q is positive definite with respect to boundedness of $\dot{e}$. Although it was shown that boundedness of $\dot{e}$ is not independent of stability, the model (11) is not correct since from (**??**) it is clear that $\dot{e}$ is a function of $\ddot{q}$ which is not a state of a robotic system. The correct representation of (11) is in the following form

$$\dot{s} = -K_1\Lambda(s)\text{sign}(s) + \Omega + e$$
$$\dot{\Omega} = -K_2\text{sign}(s) \qquad (12)$$

By considering the same Lyapunov function, its derivative is $-\eta^T Q \eta$ while the matrix Q is indefinite. This shows the stability proof is not correct.

In the sequel, this method is modified and applied to a robotic system for some particular cases. Notice that the aim is designing TDE-based controllers with precise proof of stability, and then, compare that to the state-of-the-art controllers.

C. Design of TDE-based controller

1) Case 1: Consider a robotic manipulator with the dynamic equation (1). Assume that the dynamic parameters and $\ddot{q}(t-\rho)$ are known. Additionally, presume that $\|\dot{d}\| \leq \epsilon$ with ϵ being a positive known value. The control law which is the combination of Slotine-Li controller [21] and a TDE term is given as follows

$$\tau = M\dot{\nu} + C\nu + g - KS + \hat{d}(t), \qquad (13)$$

with

$$\nu = \dot{q}_d - \Gamma\tilde{q}, \qquad S = \dot{q} - \nu, \qquad \tilde{q} = q - q_d,$$
$$\hat{d}(t) = d(t-\rho) = \tau(t-\rho) - M\ddot{q}(t-\rho)$$
$$- C(t-\rho)\dot{q}(t-\rho) - g(t-\rho), \qquad (14)$$

where $q_d \in \mathbb{R}^n$ is the desired trajectory and $\Gamma, K \in \mathbb{R}^{n \times n}$ are positive definite gains. Consider

$$V = \frac{1}{2}S^T M S, \qquad (15)$$

as a Lyapunov function candidate, it is straightforward to compute the upper bound of its derivative, which is given as

$$\dot{V} = -S^T K S - S^T(d(t) - \hat{d}(t)),$$

in which the property that $\dot{M} - 2C$ is skew-symmetric, was used. Since $\dot{d}$ is bounded, $d(t) - \hat{d}(t)$ is also bounded with the upper bound $\|d(t) - \hat{d}(t)\| \leq \rho\epsilon$. Thus

$$\dot{V} \leq -S^T K S + \rho\epsilon\|S\| \leq -\|S\|(\lambda_{min}\{K\}\|S\| - \rho\epsilon),$$

which shows that $\dot{V} \leq -\beta\|S\|^2$ if

$$\|S\| \geq \frac{\rho\epsilon}{\lambda_{min}\{K\} - \beta},$$

with β being an arbitrary small value. Hence, S and consequently $\tilde{q}$ have an ultimate bound. Since

$$\frac{1}{2}\lambda_{min}\{M\}\|S\|^2 \leq V \leq \frac{1}{2}\lambda_{max}\{M\}\|S\|^2,$$

the ultimate bound of $\|S\|$ is derived as follows

$$\|S\| \leq \sqrt{\frac{\lambda_{max}\{M\}}{\lambda_{min}\{M\}}} \frac{\rho\epsilon}{\lambda_{min}\{K\} - \beta}.$$

Note that boundedness of error is ensured in the presence of (possibly unbounded) disturbance with the expense of the precise knowledge of $\ddot{q}(t-\rho)$. This is certainly one of the superiority of the TDE-based controller compared to other reported controllers in the literature. Notice that if d is a constant external disturbance, the ultimate bound is replaced by asymptotic trajectory tracking.

2) Case 2: Now, consider a class of robotic systems in which $g(q)$ is bounded with the upper bound $\|g(q)\| \leq \kappa$. This is a very light and feasible assumption fully applicable in many case studies [22], [23]. In this case, it is possible to compensate the gravity term $g(q)$ using the TDE method. Therefore, the control law (13) is modified as follows

$$\tau = M\dot{\nu} + C\nu - KS + \hat{h}(t), \qquad (16)$$
$$\hat{h}(t) = h(t-\rho) = d(t-\rho) + g(t-\rho) = \tau(t-\rho)$$
$$- M\ddot{q}(t-\rho) - C(t-\rho)\dot{q}(t-\rho).$$

Consider (15) as the Lyapunov function candidate, and derive its derivative as:

$$\dot{V} = -S^T K S - S^T(g(t) - g(t-\rho)) - S^T(d(t)$$
$$- d(t-\rho)) \leq -\|s\|(\lambda_{min}\{K\}\|s\| - 2\kappa - \rho\epsilon),$$

where $\|g(q) - g(q-\rho)\| \leq 2\kappa$ was substituted. Hence, similar to previous case, the tracking error has an ultimate bound such that the upper bound $\|S\|$ is

$$\|S\| \leq \sqrt{\frac{\lambda_{max}\{M\}}{\lambda_{min}\{M\}}} \frac{2\kappa + \rho\epsilon}{\lambda_{min}\{K\} - \beta}.$$

Note that these two cases are applicable to regulate a robotic system without any knowledge about requirement Dynamic matrices M and C. In this situation, the control law (13) and (16) are modified respectively, as

$$\tau = -K_p\tilde{q} - K_d\dot{q} + g + \hat{d},$$

and

$$\tau = -K_p\tilde{q} - K_d\dot{q} + \hat{h},$$

with $\hat{d}$ and $\hat{h}$ defined in (14) and (16), respectively, and $0 < K_p, K_d \in \mathbb{R}^{n \times n}$. Consider

$$V = \frac{1}{2}\dot{q}^T M \dot{q} + \frac{1}{2}\tilde{q}^T K_p \tilde{q},$$

as a Lyapunov candidate, its derivative in the first case is

$$\dot{V} = -\dot{q}^T K_d \dot{q} - \dot{q}^T(d(t) - \hat{d}(t))$$
$$\leq -\|\dot{q}\|(\lambda_{min}\{K_d\}\|\dot{q}\| - \rho\epsilon),$$

and in the second case is derived as

$$\dot{V} = -\dot{q}^T K_d \dot{q} - \dot{q}^T(d(t) - \hat{d}(t)) - \dot{q}^T(g(t) - g(t-\rho))$$
$$\leq -\|\dot{q}\|(\lambda_{min}\{K_d\}\|\dot{q}\| - \rho\epsilon - 2\kappa),$$

which show that the error has an ultimate bound.

Note that in the cases where the inertia matrix or the centrifugal and Coriolis matrix are unknown, as explained in section II, it is not possible to ensure the system's stability with a TDE-based controller since the upper bound of the TDE error is related to velocity and acceleration of the system which are bounded if the manipulator is stable.

3) Case 3: The results of Case 1 are applicable to the problem of stabilization of port Hamiltonian (PH) systems with matched disturbance. Invoking [24], consider the following PH system

$$\dot{x} = [J(x) - R(x)]\nabla_x H + G(x)\big(u - d(t)\big), \qquad (17)$$

where H denotes Hamiltonian, $J = -J^T \in \mathbb{R}^{n \times n}$ is interconnection matrix, $0 \leq R(x) \in \mathbb{R}^{n \times n}$ is damping matrix, $G \in \mathbb{R}^{n \times m}$ is the input mapping matrix and d denotes external disturbance such that $\|d\| \leq \epsilon$. Assume that

$$x^* = \arg \min H(x).$$

Note that (17) may represent the closed-loop equation of nonlinear input–affine systems such as underactuated robots, see [25] for more details. Under the assumption that all the terms in (17) are known except the disturbance, the control law is given as

$$u = -KG^T\nabla_x H + \hat{d}(t)$$
$$\hat{d}(t) = d(t - \rho) = G^\dagger(t - \rho)\big(-\dot{x}(t - \rho) + [J(t - \rho)$$
$$- R(t - \rho)]\nabla_x H(t - \rho)\big) + u(t - \rho),$$

where $K \in \mathbb{R}^{m \times m}$ is positive definite gain, and $G^\dagger$ denoted the left pseudo-inverse of G. Consider H as the Lyapunov function, and find its derivative as

$$\dot{H} = -(\nabla_x H)^T\Big((R + GKG^T)\nabla_x H + Gd(t)$$
$$- Gd(t - \rho)\Big) \leq -(\nabla_x H)^T R\nabla_x H - \|(\nabla_x H)^T G\|$$
$$\big(\lambda_{min}\{K\}\|(\nabla_x H)^T G\| - \rho\epsilon\big),$$

which shows that $x - x^*$ has an ultimate bound. Clearly, if d is constant, then x^* is (asymptotically) stable. In comparison to [24], the advantage of the proposed TDE-based controller is its independence to disturbance dynamics, and the disadvantage is considering a particular disturbance and requirement to know $\dot{x}(t - \rho)$.

Based on the proposed cases, we may deduce that TDE-based controllers are practical to reject particular types of external disturbance if dynamics of the system and also $\ddot{q}(t - \rho)$ are known. Otherwise, they are not outperforming the state-of-the-art adaptive and robust controllers developed in the literature.

IV. CONCLUSION

In this note, TDE-based controllers for robotic systems were analyzed. It was elaborated that the stability proof of this method is wrong since the upper bound of TDE error is a function of the position, velocity and acceleration of the system and thus, it is bounded if system's stability is previously ensured. Furthermore, due to the representation of TDE error by a set of discrete-time linear time-varying equations, Hurwitz condition does not imply the stability.

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