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Globally Asymptotic Output Feedback Tracking of Robot Manipulators With Actuator Constraints

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Abstract: This paper revisits the problem of asymptotic tracking for robot manipulators with actuator constraints and position measurements only. A new dynamic nonlinear filter is first proposed and then a saturated output feedback proportional-derivative (PD) control is constructed. Lyapunov's direct method is employed to show global asymptotic stability (GAS). Explicit conditions on control gains ensuring GAS and avoidance of actuator constraints are obtained. This is accomplished by selecting control gains a priori. Advantage of the proposed approach is that it can assure GAS and satisfy actuator constraints. Numerical simulations are presented to demonstrate the improved performance of the proposed approach.

Keywords: Global asymptotic stability, output feedback, actuator constraints, robot control, tracking control.

1. INTRODUCTION

Trajectory tracking with an output feedback controller for robot manipulators is a challenging topic. From a theoretical point of view, the challenge lies in the fact that, generally speaking, the separation principle does not hold for such nonlinear systems. This problem is also of importance since many real-world practical robotic systems are not commonly equipped with velocity sensors; hence, full access to the system states is impossible (Nicosia & Tomei, 1990; Xian, Queiroz, Dawson, & McIntyre, 2004).

This observation is supported by several approaches for output feedback tracking control of robot manipulators. On this topic, there are two lines for pursuing the solution. In the first line, model-based observer is used to estimate the unavailable velocity signal and various observer-controller structures are proposed, see, e.g., Berghuis and Nijmeijer (1993), Bouakrif, Boukhetala, and Boudjema (2013), Canudas de Wit and Fixot (1992), Malagari and Driessen (2012), Nicosia and Tomei (1990), and the references therein. The other line focuses on filter technique. Benefitted from the easy implementation of model-free, filter-based methodology dominates the output feedback tracking of robot manipulator, see, e.g., Arteaga and Kelly (2004), Burg, Dawson, Hu, and de Queiroz, (1996), Kaneko and Horowitz (1997), Pagilla and Tomizuka (2001), Xian, Queiroz, Dawson, and McIntyre (2004), and the references within. Recently, some appealing global tracking schemes have been developed, see, e.g., Andreev and Peregudova (2019), Besancon (2000), Besancon, Battilotti, and Lanari (2003), Liuzzo and Tomei (2009), Loria (2016), Romero, Sarras, and Ortega (2015), Su and Zheng (2010), and Zhang, Dawson, de Queiroz, and Dixon (2000).

While these appealing strategies achieve satisfactory results, one major weakness remaining is that these control designs do not explicitly take actuator constraints into account. It is known that the control system design approaches that do not incorporate input constraints directly may suffer from the deteriorate performance limitations such as degraded or unpredictable motion, thermal or mechanical failure, and even instability of the controlled system (Galeani & Teel, 2006; Gayaka, Lu, & Yao, 2012; Hu & Lin, 2001).

Significant effort has been devoted to trajectory tracking of robot manipulators subject to actuator constraints, and several elegant control schemes have been developed. For example, combination of bounded regulation with a local asymptotic tracking control (Lefeber & Nijmeijer, 1997), saturated proportional-derivative (PD) plus robot dynamics control, see, e.g., Aguinga-Ruiz, Zavala-Rio, Santibanez, and Reyes (2009), and Su and Swevers (2013, 2014); saturated adaptive control, see, for instance, Dixon, de Queiroz, Zhang, and Dawson (1999), and Lopez-Araujo, Zavala-Rio, Santibanez, and Reyes (2015); saturated repetitive learning control, see, e.g., Su and Zheng (2011), and Tian and Su (2015), and sliding mode control, see, e.g., Fischer, Kan, Kamalapurkar, and Dixon (2014), and Guo, Huang, Li, and Wang (2018).

The main drawback of these strategies is that they require that both position and velocity measurements are all available for control implementation. To eliminate this drawback, a few of saturated output feedback tracking controls with position measurement only have been proposed. More specifically, Loria and Nijmeijer (1998) pioneer the work on trajectory tracking of robot manipulators subject to actuator constraints and position measurements only, and saturated output feedback PD plus robot dynamics (SOPD) control is proposed. This SOPD control is later revisited by Moreno-Valenzuela, Santibanez, and Campa (2008) and obtains exponential stability. Dixon, de Queiroz, Zhang, and Dawson (1999) propose another dynamic filter for this SOPD control.

The best result of the above mentioned approaches only assures semi-global result. As pointed by Gunawardana and Ghorbel (1999) and Kasac, Novakovic, Majetic, and Brezak (2006), it is often difficult to explicitly characterize a domain of attraction that may be much smaller than the robot workspace. This reveals that a global result is always more useful for both theoretical analysis and practical implementation. Recently, Zavala-Rio, Aguinaga-Ruiz, and Santibanez (2011) show the global asymptotic stability of the above SOPD control. But unfortunately, the proof given in that paper relies on a restrictive assumption that the inherent friction on each joints of robot is larger than the upper bound of the desired trajectory, which does not hold for general tracking problem.

In this paper, we propose a new dynamic filter and then a globally stable saturated output feedback plus robot dynamics (GSOPD) control is constructed. Global asymptotic stability is proven in agreements with Lyapunov's direct method. Numerical simulation comparison with the SOPD of (Loria & Nijmeijer, 1998) demonstrates the improved performance of the proposed approach. To the best of our knowledge, the proposed approach yields the first output feedback, global asymptotic tracking controller for general tracking problem of robot manipulators subject to position measurements only and actuator constraints. Throughout this paper, we use the notation A_m and A_M to indicate the minimum and maximum eigenvalues, respectively, of a positive definite matrix A.

2. ROBOT MODEL AND PROBLEM STATEMENT

2.1 Robot Model

The dynamics of a rigid revolute joint robot manipulator can adequately be described using Euler-Lagrange equations of motion as (Sciavicco & Siciliano, 2000)

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+g(q)=u \tag{1}$$

where $q,\dot{q},\ddot{q}\in\Re^n$ denote the link position, velocity, and acceleration, respectively, $M(q)\in\Re^{n\times n}$ represents the symmetric inertia matrix, $C(q,\dot{q})\in\Re^{n\times n}$ denotes the centrifugal-Coriolis matrix, $g(q)\in\Re^n$ is a gravity force, and $u\in\Re^n$ denotes the torque input vector. Recalling the robot manipulators are being considered, the following properties can be established (Sciavicco & Siciliano, 2000).

Property 1. The inertia matrix $M(q)$ is symmetric positive definite and satisfies the following inequality:

$$m_1\|\xi\|^2\le\xi^T M(q)\xi\le m_2\|\xi\|^2,\quad\forall\xi\in\Re^n \tag{2}$$

where m_1 and m_2 are known positive constants.

Property 2. There exists a positive constant k_c such that

$$\|C(q,\dot{q})\|\le k_c\|\dot{q}\|,\ \forall q,\dot{q}\in\Re^n \tag{3}$$

Property 3. The vector $g(q)$ is upper bounded by

$$\|g(q)\|\le\kappa_g \tag{4}$$

with κ_g is a known positive constant.

Property 4. The centrifugal-Coriolis matrix $C(q,\dot{q})$ satisfies

$$C(q,\xi)\vartheta=C(q,\vartheta)\xi,\qquad\forall q,\xi,\ \vartheta\in\Re^n \tag{5}$$

Property 5. The matrix $C(q,\dot{q})$ is defined using Christoffel symbols, and $\dot{M}(q)-2C(q,\dot{q})$ is skew-symmetric, i.e.

$$\zeta^T\left(\dot{M}(q)-2C(q,\dot{q})\right)\zeta=0,\ \forall\zeta\in\Re^n \tag{6}$$

2.2 Problem Statement

Let $q_d\in\Re^n$ be any continuous reference trajectory for robotic system (1) satisfying

$$\|\dot{q}_d\|\le V_M,\|\ddot{q}_d\|\le A_M \tag{7}$$

where V_M and A_M are two known positive constants.

The position tracking error $e(t)\in\Re^n$ is defined as

$$e=q-q_d \tag{8}$$

Similar to Loria and Nijmeijer (1998), to ensure global asymptotic tracking, it is assumed that each actuator has a maximum allowable torque $u_{i,\max}$ satisfying

$$u_{i,\max}>m_2A_M+k_cV_M^2+k_g \tag{9}$$

The objective of this paper is to design a saturated output feedback control input u with position measurements only and satisfying the actuator constraint

$$|u_i|\le u_{i,\max} \tag{10}$$

such that $e(t)\to 0$ and $\dot{e}(t)\to 0$ as $t\to\infty$ for any initial state $(q(0),\dot{q}(0))$, where u_i denotes the ith component of the control input u.

3. CONTROL DEVELOPMENT

3.1 Control Formulation

To aid the subsequent control design, we define the vector $\mathrm{Tanh}(\cdot)\in\Re^n$ and the diagonal matrix $\mathrm{Sech}(\cdot)\in\Re^{n\times n}$ as follows:

$$\mathrm{Tanh}(\xi)=\left[\tanh(\xi_1),\cdots,\tanh(\xi_n)\right]^T \tag{11}$$

$$\mathrm{Sech}(\xi)=\mathrm{diag}\left(\mathrm{sech}(\xi_1),\cdots,\mathrm{sech}(\xi_n)\right) \tag{12}$$

where $\xi=\left[\xi_1,\cdots,\xi_n\right]^T\in\Re^n$, $\tanh(\cdot)$ and $\mathrm{sech}(\cdot)$ being the standard hyperbolic tangent and secant functions, respectively, and $\mathrm{diag}(\cdot)$ denotes a diagonal matrix.

Let us define a filtered tracking error $\eta\in\Re^n$ as follows:

$$\eta=\dot{e}+\alpha\mathrm{Tanh}(e)+\alpha\mathrm{Tanh}(\upsilon) \tag{13}$$

with $\upsilon\in\Re^n$ is an auxiliary filter variable defined by (14), and $\alpha<1$ is a positive constant.

The globally stable saturated output feedback PD plus robot dynamics (GSOPD) control is proposed as follows:

$$u = M(q)\ddot{q}_d + C(q,\dot{q}_d)\dot{q}_d + g(q) + K_d \mathrm{Tanh}(\upsilon) - K_p \mathrm{Tanh}(e) \tag{14}$$

$$\dot{\upsilon} = -\mathrm{Sech}^{-2}(\upsilon)(K_0\eta + K_1 \mathrm{Tanh}(\upsilon)),\ \upsilon(0) = 0 \tag{15}$$

where $K_0, K_1, K_p, K_d \in \Re^{n\times n}$ are constant positive definite diagonal matrices.

Remark 1. From the definition of η given by (13), it seems that velocity measurements are required for control implementation in (14) and (15). However, after the stability proof, we will illustrate how the proposed controller can be implemented with sole position measurements.

Remark 2. By virtue of (2)–(4) of Properties 1–3 and upper bounds on the reference trajectory given by (7), the control effort defined by (14) can be easily upper bounded by

$$|u_i| \le m_2 A_M + k_c V_M^2 + \kappa_g + k_{pi} + k_{di} \tag{16}$$

where k_{pi} and k_{di} are the ith elements of the constant positive definite diagonal matrices K_p and K_d, respectively.

Hence, the actuator saturation can be completely avoided by selecting the control gains a priori to satisfy the following constraints

$$k_{pi} + k_{di} < u_{i,\max} - (m_2 A_M + k_c V_M^2 + k_g) \tag{17}$$

Upon taking the time derivative of (13) and multiplying $M(q)$ to both sides of the resulting equation, we have

$$M(q)\dot{\eta} = M(q)\ddot{e} + \alpha M(q)\mathrm{Sech}^2(e)\dot{e} + \alpha M(q)\mathrm{Sech}^2(\upsilon)\dot{\upsilon} \tag{18}$$

After applying the definition of (8) to (18) and substituting the control law (14) and (15) into the resulting equation, the closed-loop dynamics for η take

$$M(q)\dot{\eta} = -C(q,\dot{q})\eta - \alpha K_0 M(q)\eta + N_1 + N_2 - K_d \mathrm{Tanh}(\upsilon) - K_p \mathrm{Tanh}(e) \tag{19}$$

where the residual dynamics $N_1(e,\upsilon,\eta), N_2(e,\upsilon,\eta) \in \Re^n$ are defined as

$$N_1 = \alpha M(q)\mathrm{Sech}^2(e)(\eta - \alpha\mathrm{Tanh}(e) - \alpha\mathrm{Tanh}(\upsilon)) - \alpha M(q) K_1 \mathrm{Tanh}(\upsilon) \tag{20}$$

$$N_2 = C(q,\dot{q})(\eta - \dot{q}) + C(q,\dot{q}_d)\dot{q}_d \tag{21}$$

where the fact that $\dot{e} = \eta - \mathrm{Tanh}(e) - \alpha\mathrm{Tanh}(\upsilon)$ from (13) is used for (20).

By the definitions of (8) and (13), we can rewrite (21) as

$$N_2 = C(q,\dot{q}_d + \eta - \alpha\mathrm{Tanh}(e) - \alpha\mathrm{Tanh}(\upsilon)) \times(-\dot{q}_d + \alpha\mathrm{Tanh}(e) + \alpha\mathrm{Tanh}(\upsilon)) + C(q,\dot{q}_d)\dot{q}_d \tag{22}$$

Recalling (5) of Property 5, we can rewrite (21) as

$$N_2 = C(q,\eta - \alpha\mathrm{Tanh}(e) - \alpha\mathrm{Tanh}(\upsilon)) \times(-\dot{q}_d + \alpha\mathrm{Tanh}(e) + \alpha\mathrm{Tanh}(\upsilon)) + \alpha C(q,\dot{q}_d)(\mathrm{Tanh}(e) + \mathrm{Tanh}(\upsilon)) \tag{23}$$

Remark 3. By the properties of the standard hyperbolic tangent and secant functions and (7) on the desired continuous reference trajectory, it is easy to find that the residual dynamics N_1 and N_2 can be upper bounded by

$$\|N_1\| \le \alpha m_2\|\eta\| + \alpha^2 m_2\|\mathrm{Tanh}(e)\| + \alpha(K_{1M} + \alpha)m_2\|\mathrm{Tanh}(\upsilon)\| \tag{24}$$

$$\begin{aligned}\|N_2\| &\le k_c\|\eta - \alpha\mathrm{Tanh}(e) - \alpha\mathrm{Tanh}(\upsilon)\| \\ &\quad\times\|-\dot{q}_d + \alpha\mathrm{Tanh}(e) + \alpha\mathrm{Tanh}(\upsilon)\| \\ &\quad+ \alpha k_c\|\dot{q}_d\|\|\mathrm{Tanh}(e) + \mathrm{Tanh}(\upsilon)\| \\ &\le a_0\|\eta\| + \alpha a_1(\|\mathrm{Tanh}(e)\| + \|\mathrm{Tanh}(\upsilon)\|)\end{aligned} \tag{25}$$

and the positive constants a_0 and a_1 are defined as

$$a_0 = (V_M + 2\alpha\sqrt{n})k_c \tag{26}$$

$$a_1 = 2(V_M + \alpha\sqrt{n})k_c \tag{27}$$

where we have utilized the fact that $\|\mathrm{Tanh}(\xi)\| \le \sqrt{n}$ from the definition of (11) and the hyperbolic tangent function.

3.2 Stability Analysis

We are now in a position to state the following theorem.

Theorem 1. Given the robot dynamics of (1) and the desired continuous trajectory satisfying (7), the proposed output feedback control given by (14)–(15) can avoid actuator saturation completely and assure the global asymptotic stability, provided the control gains are chosen to satisfy the constraint (17) and the following sufficient conditions:

$$K_{0m} > \frac{1}{2}m_1^{-1}((K_{1M} + 2(1+\alpha))m_2 + 2\alpha^{-1}a_0 + 2a_1) \tag{28}$$

$$K_{pm} > \frac{1}{2}(K_{pM} + \alpha m_2 + a_1) \tag{29}$$

$$K_{1m} > \frac{1}{2}\alpha(K_d K_0^{-1})_m^{-1}(K_{pM} + (K_{1M} + \alpha)m_2 + a_1) \tag{30}$$

Proof. Theorem 1 is proved following Lyapunov's direct method. For this purpose, the Lyapunov function candidate V is proposed as follows

$$V = \frac{1}{2}\eta^T M(q)\eta + \sum_{i=1}^{n} k_{pi}\ln(\cosh(e_i)) + V_0 \tag{31}$$

with V_0 is defined as

$$\begin{aligned}V_0 &= \int_0^{\upsilon} \mathrm{Tanh}^T(\sigma)K_d K_0^{-1}\mathrm{Sech}^2(\sigma)d\sigma \\ &= \sum_{i=1}^{n}\int_0^{\upsilon_i} k_{di}k_{0i}^{-1}\mathrm{sech}^2(\sigma)\tanh(\sigma)d\sigma\end{aligned} \tag{32}$$

where $\ln(\cdot)$ and $\cosh(\cdot)$ being the standard natural logarithm and hyperbolic cosine functions, respectively, and k_{0i} is the ith element of the positive definite diagonal matrix K_0.

Following the arguments in (Su & Zheng, 2010), it is easy to show that

$$V_0 = \int_0^{\upsilon} \mathrm{Tanh}^T(\sigma) K_d K_0^{-1} \mathrm{Sech}^2(\sigma) d\sigma > 0 \text{ for } \upsilon \neq 0 \tag{33}$$

because $\mathrm{Sech}^2(\upsilon)$, K_0 and K_d are all diagonal positive definite matrices, and the facts that $\mathrm{Tanh}(0) = 0$, $\mathrm{Sech}^2(0) = 1$, and the entries $\tanh(\upsilon_i)$ of $\mathrm{Tanh}(\upsilon)$ are increasing functions with respect to υ_i from the properties of hyperbolic secant and tangent functions.

As a result, from (2) of Property 1 and the properties of the standard natural logarithm and hyperbolic cosine functions, we can conclude that the proposed V is radially unbounded and positive definite with respect to η, e, υ

After taking the first time derivative of (31) along the closed-loop system (19), we have

$$\begin{aligned} \dot{V} &= \frac{1}{2}\eta^T \dot{M}(q)\eta + \eta^T M(q)\dot{\eta} + \mathrm{Tanh}^T(e) K_p \dot{e} \\ &\quad + \mathrm{Tanh}^T(\upsilon) K_d K_0^{-1} \mathrm{Sech}^2(\upsilon)\dot{\upsilon} \end{aligned} \tag{34}$$

Upon substituting $M(q)\dot{\eta}$ from (19) and $\dot{\upsilon}$ from (15) into (34) and recalling (6) of Property 5, it follows that

$$\begin{aligned} \dot{V} &= \eta^T(-\alpha K_0 M(q)\eta + N_1 + N_2 + K_d \mathrm{Tanh}(\upsilon) - K_p \mathrm{Tanh}(e)) \\ &\quad + \mathrm{Tanh}^T(e) K_p \dot{e} + \mathrm{Tanh}^T(\upsilon) K_d K_0^{-1} \mathrm{Sech}^2(\upsilon)\dot{\upsilon} \end{aligned} \tag{35}$$

After applying the definition of η in (13) and the filter (15) to (35) yields

$$\begin{aligned} \dot{V} &= -\alpha\eta^T K_0 M(q)\eta - \alpha \mathrm{Tanh}^T(e) K_p \mathrm{Tanh}(e) \\ &\quad - \mathrm{Tanh}^T(\upsilon) K_1 K_d K_0^{-1} \mathrm{Tanh}(\upsilon) + \eta^T(N_1 + N_2) \\ &\quad - \alpha \mathrm{Tanh}^T(\upsilon) K_p \mathrm{Tanh}(e) \end{aligned} \tag{36}$$

Obviously, by virtue of (2) of Property 1 and substituting the upper bounds on N_1 and N_2 given in Remark 3 into (36), we have

$$\begin{aligned} \dot{V} &\leq -\alpha m_1 K_{0m} \|\eta\|^2 - K_{1m}(K_d K_0^{-1})_m \|\mathrm{Tanh}(\upsilon)\|^2 \\ &\quad + (\alpha m_2 + a_0)\|\eta\|^2 + \alpha(\alpha m_2 + a_1)\|\eta\|\|\mathrm{Tanh}(e)\| \\ &\quad + \alpha((K_{1M} + \alpha)m_2 + a_1)\|\eta\|\|\mathrm{Tanh}(\upsilon)\| \\ &\quad - \alpha K_{pm}\|\mathrm{Tanh}(e)\|^2 + \alpha K_{pM}\|\mathrm{Tanh}(e)\|\|\mathrm{Tanh}(\upsilon)\| \end{aligned} \tag{37}$$

After multiple applying the triangle inequality $bc \leq (b^2 + c^2)/2$ to (37) with $b = \|\eta\|$ and $c = \|\mathrm{Tanh}(\upsilon)\|$ and $c = \|\mathrm{Tanh}(e)\|$, and $b = \|\mathrm{Tanh}(e)\|$ and $c = \|\mathrm{Tanh}(\upsilon)\|$, respectively, it leads to

$$\begin{aligned} \dot{V} &\leq -\frac{\alpha}{2}\left[2m_1 K_{0m} - ((K_{1M} + 2(1+\alpha))m_2 + 2\alpha^{-1}a_0 + 2a_1)\right]\|\eta\|^2 \\ &\quad - \frac{\alpha}{2}\left[2K_{pm} - (K_{pM} + \alpha m_2 + a_1)\right]\|\mathrm{Tanh}(e)\|^2 \\ &\quad - \frac{1}{2}\left[2K_{1m}(K_d K_0^{-1})_m - \alpha(K_{pM} + (K_{1M} + \alpha)m_2 + a_1)\right] \\ &\qquad \times \|\mathrm{Tanh}(\upsilon)\|^2 \end{aligned} \tag{38}$$

In the light of the conditions (28)–(30) in Theorem 1, it is clear that V is a radially unbounded positive definite Lyapunov function whose time derivative $\dot{V}$ is negative definite. Hence, by Lyapunov's direct method (Slotine & Li, 1991), the result shown in Theorem 1 directly follows. This completes the proof. □

Remark 4. Comparing with the semi-global asymptotic stability of (Loria & Nijmeijer, 1998), this paper shows more desirable global asymptotic stability (GAS). Moreover, this paper obtains explicit conditions on control gains for ensuring GAS and completely avoidance of actuator constraints. In comparison, the conditions given in (Loria & Nijmeijer, 1998) are too complicated and not easy to implement.

3.3 Practical Implementation

In this section, we illustrate how the proposed output feedback control law given by (14)–(15) can be implemented with position measurements only. Note that the torque control input given by (14) does not require the computation of υ; rather, only $\mathrm{Tanh}(\upsilon)$. Hence, introduce an auxiliary variable $r \in \Re^n$ as follows

$$r = \mathrm{Tanh}(\upsilon), \quad \upsilon(0) = 0 \tag{39}$$

It is obvious that

$$\dot{r} = \mathrm{Sech}^2(\upsilon)\dot{\upsilon}, \quad r(0) = 0 \tag{40}$$

Note that in the derivation of the initial value of r we have utilized the fact that $\mathrm{Tanh}(0) = 0$ from the property of the standard hyperbolic tangent function.

Upon substituting $\dot{\upsilon}$ from (15) into (40) and recalling (39), it follows that

$$\dot{r} = -K_0\eta - K_1 \mathrm{Tanh}(\upsilon), \quad r(0) = 0 \tag{41}$$

After applying the definitions of η in (13) and r in (39) to (41), leads to

$$\dot{r} = -K_0\dot{e} - \alpha K_0 \mathrm{Tanh}(e) - (\alpha K_0 + K_1)r, \quad r(0) = 0 \tag{42}$$

From (42), it is obvious that r can be calculated with e by

$$\begin{cases} r = q_c - K_0 e \\ \dot{q}_c = -\alpha K_0 \mathrm{Tanh}(e) - (\alpha K_0 + K_1)r, \quad q_c(0) = K_0 e(0) \end{cases} \tag{43}$$

with $q_c \in \Re^n$ is another auxiliary variable.

Remark 5. Similar to Zhang, Dawson, de Queiroz, and Dixon (2000) and Su and Zheng (2010), observe that $|r_i| \le 1$ hold true for all $r_i(0) = 0$ and $t > 0$, where r_i denotes the ith element of the vector r defined by (39).

Thanks to (43), the proposed GSOPD control given by (14)–(15) can be implemented with position measurements only as

$$u = M(q)\ddot{q}_d + C(q,\dot{q}_d)\dot{q}_d + g(q) + K_d r - K_p \mathrm{Tanh}(e) \tag{44}$$

4. AN ILLUSTRATIVE EXAMPLE

Simulation comparison on an illustrative example used in (Loria & Nijmeijer, 1998) is performed to show the improved performance of the proposed approach. The entries to model the robot are, respectively (Loria & Nijmeijer, 1998)

$$\begin{aligned} M(q) &= \begin{bmatrix} p_1 + 2p_2\cos(q_2) & p_3 + p_2\cos(q_2) \\ p_3 + p_2\cos(q_2) & p_4 \end{bmatrix} \\ C(q,\dot{q}) &= \begin{bmatrix} -p_2\sin(q_2)\dot{q}_2 & -p_2\sin(q_2)(\dot{q}_1 + \dot{q}_2) \\ p_2\sin(q_2)\dot{q}_1 & 0 \end{bmatrix} \\ g(q) &= [p_5\sin(q_1) + p_6\sin(q_1+q_2),\ p_6\sin(q_1+q_2)]^T \end{aligned} \tag{45}$$

with $p_1 = 8.77$, $p_2 = 0.51$, $p_3 = 0.76$, $p_4 = 0.62$, $p_5 = 74.48$, and $p_6 = 6.174$. The parameters in the simulations are given in SI units.

The control input of the SOPD controller presented in (Loria & Nijmeijer, 1998) is the same as (14) with the following filter

$$\begin{cases} \upsilon = q_c + Be \\ \dot{q}_c = -A\mathrm{Tanh}(\upsilon),\ q_c(0) = -Be \end{cases} \tag{46}$$

where A and B are constant positive definite diagonal filter gain matrices.

The maximum allowable torque is $u_{1,\max} = u_{2,\max} = 350$ Nm , the desired trajectory is $q_d = (\sin(\pi t), \sin(\pi t))^T$ (rad) , and the initial conditions are $[q(0)^T, \dot{q}(0)^T]^T = [3.0, -2.0, 0, 0]^T$. The sampling period is $T = 1$ ms . By inserting the parameters given in (46) and the desired trajectory, the upper bounds for determining the control gains are given as

$$m_1 = 8.3,\ m_2 = 10.0,\ k_c = 1.0,\ k_g = 80.66 \tag{47}$$

$$V_M = 4.5,\ A_M = 14.0 \tag{48}$$

With the above bounds, it is easy to verify that the constraints on the control gains are $k_{pi} + k_{di} < 114$. Hence, the control gains of the SOPD are as $K_p = \mathrm{diag}(73,73), K_d = \mathrm{diag}(40,40)$, $A = \mathrm{diag}(120,120)$, and $B = \mathrm{diag}(110,110)$. According to the conditions (26)–(28) given in Theorem 1 and the aforementioned constraints, the gains of the proposed GSOPD control are chosen as $\alpha = 0.03$, $K_0 = \mathrm{diag}(45,45)$, $K_1 = \mathrm{diag}(40,40)$, $K_p = \mathrm{diag}(80,100)$, and $K_d = \mathrm{diag}(33,10)$.

The position tracking errors are shown in Fig. 1. For a clear view, the requested control inputs are illustrated in Figs. 2 and 3, respectively. Clearly, both controls successfully complete the movement of the robot with asymptotic tracking after a transient due to large errors in initial condition. Obviously, the proposed GSOPD control obtains a faster transient over the SOPD control. Both of the required inputs of these two controls keep in the maximum allowable limit.

5. CONCLUSIONS

This paper revisits asymptotic tracking of robot manipulators with actuator constraints and position measurements only. A new dynamic nonlinear filter is proposed and a saturated output feedback PD control plus robot dynamics is constructed. Global asymptotic tracking stability is proven with Lyapunov's direct method. Explicit conditions on control gains are obtained for ensuring global asymptotic stability and avoidance of actuator saturation. Numerical simulation comparison shows the faster transient of the proposed approach.

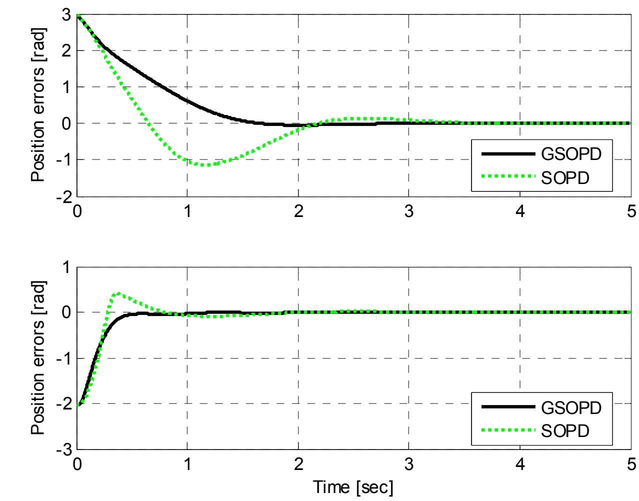

Fig. 1 Position tracking errors.

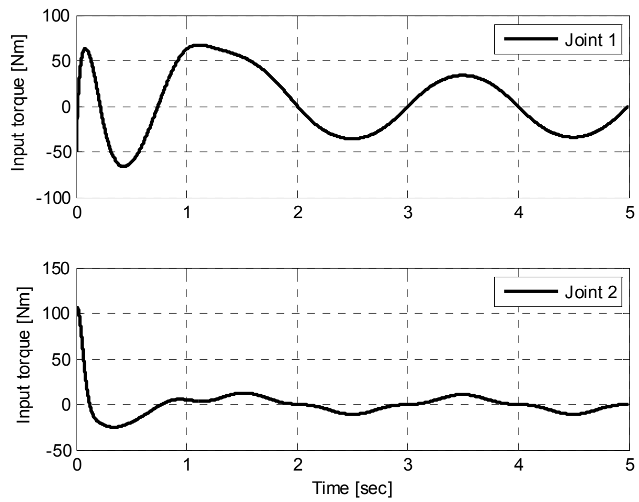

Fig. 2. Requested inputs of GSOPD control.

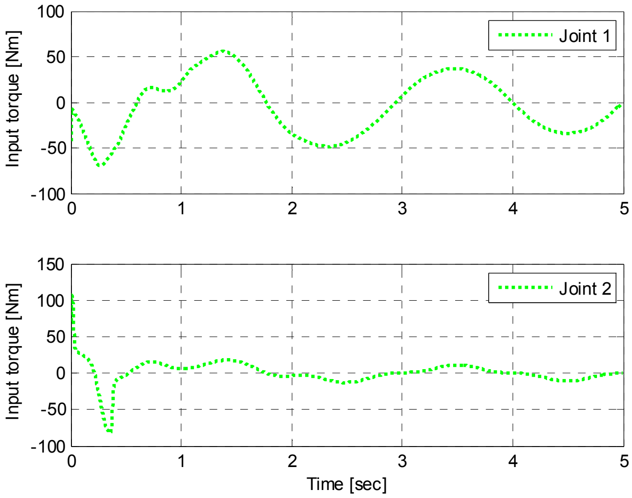

Fig. 3. Requested inputs of SOPD control.

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