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Simple Saturated PID Control for Fast Transient of Motion Systems

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Abstract: This paper proposes a simple saturated proportional-integral-derivative (PID) control for set-point stabilization of motion systems subject to actuator constraint. The proposed controller consists of a saturated proportional-derivative (PD) term and a saturated integral (I) term that robustly compensates the constant or slow time-varying unknown disturbances. It is shown that the proposed saturated PID (SPID) controller globally asymptotic stabilizes the set-point of motion systems without violation of actuator constraint. The appealing feature of the proposed approach is that it embeds the PD term within a single saturation function, which allows us to choose the proportional and derivative gains freely for faster transient and higher steady-state set-point precision. Numerical comparisons of an illustrative example demonstrate the improved performance of the proposed approach.

Keywords: Actuator constraint, proportional-integral-derivative (PID) control, motion systems, asymptotic stabilization.

1. INTRODUCTION

Motion systems have been widely applied in industrial automation fields. Set-point is the simplest aim in motion control and at the same time one of the most relevant issues in practice (Bucci, Cole, Ludwick, & Vipperman, 2013; Ohnishi, Shibata, & Murakami, 1996). Although the modern control theory has achieved considerable progress, so far most industrial motion systems are still controlled with PID/PD controllers, due mostly to their conceptual simplicity, model-free formulation, and explicit tuning procedures (Bisoffi, Da Lio, Teel, & Zaccarian, 2018; Putra, Nijmeijer, & van de Wouw, 2007; Su, Müller, & Zheng, 2010).

To improve the performance of the classical PID control, significant effort has been devoted and some nonlinear PID/PD structures have been proposed. More specifically, several variable-gain linear controls for fast transient of motion systems can be found in the literature (Armstrong, Guitierrez, Wade, & Joseph, 2006; Hunnekens, van de Wouw, Heertjes, & Nijmeijer, 2015; van de Wouw, Pastink, Heertjes, Pavlov, & Nijmeijer, 2008). Recognizing the advantages of high robustness against uncertainties and disturbances, impulsive control is introduced to improve the performance of the classical PID/PD control (Orlov, Santiesteban, & Aguilar, 2009; van de Wouw & Leine, 2012). Switching control offers an alternative solution to an improved PID/PD control for motion systems. Such examples include switching PID control (Beerens, Nijmeijer, Heemels, & van de Wouw, 2017) and adding a relay-like term to the commonly-used PD control (Zheng, Su, & Mercorelli, 2018). Recently, to improve the convergence of PID controlled motion systems with friction, several appealing reset schemes have been proposed (see, e.g., Aangenent, Witvoet, Heemels, van de Molengraft, & Steinbuch, 2010; Beerens, Bisoffi, Zaccarian, Heemels, Nijmeijer, & van de Wouw, 2019; van Loon, Hunnekens, Heemels, van de Wouw, & Nijmeijer, 2016).

While these elegant schemes achieve satisfactory results, one major drawback remaining is that the control designs do not take into account actuator constraint. It is known that the control system design approaches that do not incorporate input constraint 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).

This observation is supported by several works on high-precision set-point of motion systems subject to actuator constraint. In particular, Workman (1987) pioneers a proximate time-optimal (PTO) scheme for servomechanisms to overcome the effect of actuator saturation. This seminal work is later extended in several directions and various interesting PTO controls have been proposed (Cheng & Hu, 2014; Salton, Al-Ghanimi, Flores, Zheng, Gomes da Silva, & Fu, 2017; Salton, Chen, & Fu, 2012). The other efforts on the composite nonlinear feedback (CNF) methodology for fast and accuracy control of motion systems with actuator constraint can be found in the literature, see, e.g., Chen, Lee, Peng, and Venkataramanan (2003), Cheng and Peng (2007), Peng, Chen, Cheng, and Lee (2005), and the references therein. The weakness of these saturated controls is that they require the system parameters to be known exactly.

Recently, a simple model-free saturated PD control is proposed for an improved set-point of motion systems with actuator constraint (Zheng, Su, & Mercorelli, 2019a). The minor weakness is that the friction is not considered. This favourable result is later extended by adding a robust term to compensate the effect of nonlinear friction (Zheng, Su, &

Mercorelli, 2019b, c). The main drawback of these model-free saturated control techniques is that the persistent injection of high frequency robust control signals may excite unmodeled high-frequency system dynamics, which is highly undesirable in motion systems, and, therefore, these techniques are not appealing for being used in industrial applications (Beerens, Bisoffi, Zaccarian, Heemels, Nijmeijer, & van de Wouw, 2019).

In this paper, we propose a simple but quite effective saturated PID (SPID) control for motion systems subject to actuator constraint and constant or slow time-varying disturbance. The proposed SPID control is constructed within the framework of model-free nonlinear PID (NPID) control methodology with simple and intuitive structure, and thus it permits easy implementation. The proposed control embeds the PD action within a single saturation function and utilizes a saturated integral term to compensate the effect of the constant or slow time-varying unknown disturbances. Benefitting from such design, it completes remove elaborated discrimination of the terms of the commonly-used saturated controls that shall be bounded and permits free choice of proportional and derivative gains, and thus it is ready for implementation with faster transient and higher steady-state set-point precision. Global asymptotic stabilization is proven following Lyapunov's direct method and LaSalle's invariance principle. The conditions on control gains ensuring global asymptotic stability are obtained. The effectiveness and improved performance of the proposed approach is demonstrated by numerical simulations performed on a servo system used in (Cheng & Peng, 2007).

2. PROBLEM STATEMENT

Similar to (Cheng & Peng, 2007; Peng, Chen, Cheng, & Lee, 2005), consider the following motion system

$$J\ddot{q} = u - b\dot{q} + d \tag{1}$$

where J is the positive inertia (or mass), q and $\dot{q}$ denote the angular position (or position) and angular velocity (or velocity), u is the control input, b denotes the viscous damping friction coefficient, and d is a bounded unknown constant or slow time-varying disturbance.

For our purpose, the following assumption is required.

Assumption 1. We assume that the actuator has a maximum torque $u_{\max}$ satisfying

$$u_{\max} > d_m \tag{2}$$

where d_m is a known positive constant such that $|d| \le d_m$.

For a given desired constant position q_d for the motion system defined by (1), our objective in this paper is to design a very simple model-free high computational efficient saturated PID control satisfying the actuator constraint

$$|u| \le u_{\max} \tag{3}$$

such that the system is global asymptotic stable with an improved performances including fast transient and high steady-state set-point precision.

To quantify this objective, a set-point error $e(t)$ is defined as

$$e = q - q_d \tag{4}$$

Our proposed control explores on the following lemma.

Lemma 1 (Su, Zheng, & Mercorelli, 2017). *For any $x, y \in \Re$, a strictly increasing saturation function $\sigma(x)$ ensures that $y(\sigma(x+y)-\sigma(x)) > 0$ if $y \ne 0$ and $y(\sigma(x+y)-\sigma(x)) = 0$ if and only if $y = 0$.*

3. CONTROL DEVELOPMENT

3.1 Control formulation

Following (Zheng, Su, & Mercorelli, 2018, 2019a), we first define a nonlinear function as follows

$$s(x) = \begin{cases} |x|^{\alpha}\,\mathrm{sgn}(x), & |x| > \delta \\ \delta^{\alpha-1}x, & |x| \le \delta \end{cases} \tag{5}$$

where $\alpha, \delta \in (0, 1]$ are parameters to be designed, and $\mathrm{sgn}(\cdot)$ is the standard signum function.

Lemma 2 (Zheng, Su, & Mercorelli, 2018). *The nonlinear function $s(x)$ has the following properties:*

1) *$s(x)$ is strictly increasing in x and $s(x) = 0$ only for $x = 0$;*
2) *For all $x \ne 0$, the following fact holds true*

$$xs(x) \ge s(x)\tanh(x) \ge \tanh^2(x) > 0 \tag{6}$$

where $\tanh(\cdot)$ is the standard hyperbolic tangent function.

We now propose the following simple model-free saturated PID (SPID) control to solve the above stated problem:

$$u = -a_m \tanh(k_p s(e) + k_d \dot{q}) - k_i \tanh(y) \tag{7}$$

$$y = \int_0^t [\dot{q}(\tau) + \lambda \tanh(e(\tau))]d\tau \tag{8}$$

where k_p, k_i, and k_d are positive proportional, integral, and derivative gains, respectively, and a_m and λ are two positive constants.

Remark 1. Different to the aforementioned well-known PTO and CNF strategies for motion systems, the proposed SPID control is constructed in the framework of NPID methodology, which is complete model-free with intuitive structure, and this it is easy to implement in practice. In comparison with our saturated controls (Zheng, Su, & Mercorelli, 2019b, c), a saturated integral action is introduced and the proposed control is absolute continuous, and hence it removes the potential chattering of (Zheng, Su, & Mercorelli, 2019b, c) resulted from the discontinuous robust compensation involving signum function and thus it is quite appealing for being used in industrial applications.

It is clear from (7) that the control effort of the proposed SPID control can be explicitly upper bounded by

$$|u| \le a_m + k_i \tag{9}$$

To facilitate the following analysis, let us define a filtered positioning error as follows:

$$\eta = \dot{e} + \lambda \tanh(e) \tag{10}$$

Now the error system development is first conducted by calculating the open-loop filtered error dynamics. To this end, taking the time derivative of (10) yields

$$\dot{\eta} = \ddot{e} + \lambda \mathrm{sech}^2(e)\dot{e} \tag{11}$$

where $\mathrm{sech}(\cdot)$ is the standard hyperbolic secant function.

Multiplying both sides of (11) by J and then substituting $J\ddot{q}$ from (1) into the resulting expression, it follows that

$$J\dot{\eta} = u - b\dot{q} + d + \lambda J \mathrm{sech}^2(e)\dot{q} \tag{12}$$

where we have invoked the facts that $\ddot{e} = \ddot{q}$ and $\dot{e} = \dot{q}$ for set-point control.

Upon introducing a new variable

$$z = \tanh(y) - k_i^{-1} d \tag{13}$$

and substituting the proposed control (7) into (12), the closed-loop dynamics for η take

$$J\dot{\eta} = -a_m \tanh(k_p s(e) + k_d \dot{q}) - (b - \lambda J \mathrm{sech}^2(e))\dot{q} - k_i z \tag{14}$$

After adding the term $k_d \eta$ and subtracting the equivalent term $k_d(\dot{e} + \lambda \tanh(e))$ (by the definition of η of (10)) to the first term of the right-hand side (RHS) of (14), we have

$$\begin{aligned} J\dot{\eta} = &-a_m \tanh(k_d \eta + k_p s(e) - \lambda k_d \tanh(e)) \\ &- (b - \lambda J \mathrm{sech}^2(e))\dot{q} - k_i z \end{aligned} \tag{15}$$

where the fact that $\dot{e} = \dot{q}$ for set-point control is used.

Now let us define an auxiliary function $\varphi(e)$ as follows

$$\varphi(e) = k_p s(e) - \lambda k_d \tanh(e) \tag{16}$$

After adding and subtracting the term $a_m \tanh(\varphi(e))$ to the RHS of (15), it follows that

$$\begin{aligned} J\dot{\eta} = &-a_m [\tanh(k_d \eta + \varphi(e)) - \tanh(\varphi(e))] \\ &- a_m \tanh(\varphi(e)) - (b - \lambda J \mathrm{sech}^2(e))\dot{q} - k_i z \end{aligned} \tag{17}$$

where we have invoked (16).

3.2 Stability analysis

Now we are in a position to present the following theorem.

Theorem 1. *Given the uncertain motion systems subject to actuator constraint and bounded unknown constant or slow time-varying disturbances described by (1) and the desired constant position q_d, the proposed SPID control defined by (7) and (8) ensures global asymptotic set-point stability and completely avoids actuator saturation, provided the control gains are chosen to satisfy the following sufficient conditions:*

$$k_i \ge d_m \tag{18}$$

$$a_m + k_i < u_{\max} \tag{19}$$

$$0 < \lambda < \min\left\{\frac{k_p}{k_d}, \frac{b}{J}\right\} \tag{20}$$

Proof. The proof proceeds with Lyapunov's direct method and LaSalle's invariance principle. For this purpose, the Lyapunov function candidate is proposed as

$$V = \frac{1}{2} J \eta^2 + V_1 + V_2 + V_3 \tag{21}$$

with $V_i, i = 1, 2, 3$ are, respectively, defined as

$$V_1 = a_m \int_0^e \tanh(\varphi(\tau)) d\tau \tag{22}$$

$$V_2 = \lambda \int_0^e (b - \lambda J \mathrm{sech}^2(\tau)) \tanh(\tau) d\tau \tag{23}$$

$$V_3 = k_i \int_0^z \mathrm{sech}^{-2}(\mathrm{atanh}(\tau + k_i^{-1} d)) \tau d\tau \tag{24}$$

where $\mathrm{atanh}(\cdot)$ being the standard inverse hyperbolic tangent function.

To show the radially unbounded and positive definiteness of V, we first consider V_1 defined by (22). By virtue of property (6) in Lemma 2 and the condition (20) on λ (i.e. $k_p > \lambda k_d$), it is easy to verify that

$$\varphi(e)e > 0 \text{ for } e \ne 0, \text{ and } \varphi(e)e = 0 \text{ only for } e = 0 \tag{25}$$

This fact together with the property of the standard hyperbolic tangent function allows us to conclude that V_1 is radially unbounded and positive definite with respect to (w.r.t.) e. Similarly, by condition (20) on λ (i.e. $b > \lambda J$) and the fact that $-\lambda J \mathrm{sech}^2(\tau) \ge -\lambda J$ from the property of the standard hyperbolic secant function, V_2 is also radially unbounded and positive definite w.r.t. e.

In the light of the fact that $\mathrm{sech}^{-2}(\cdot)$ is positive and the property of the calculus, it is straightforward to have the fact that V_3 defined by (24) is radially unbounded and positive definite w.r.t. e. Finally, invoking the positive property of the inertia J, it can conclude that the V given by (21) is radially unbounded and positive definite w.r.t. η, e.

Upon taking the time derivative of V along (17) yields

$$\begin{aligned} \dot{V} = &J\eta\dot{\eta} + a_m \tanh(\varphi(e))\dot{e} + \lambda(b - \lambda J \mathrm{sech}^2(e)) \tanh(e)\dot{e} \\ &+ k_i \mathrm{sech}^{-2}(\mathrm{atanh}(z + k_i^{-1} d)) z\dot{z} \end{aligned} \tag{26}$$

By the definition of z in (13) and the assumption on the disturbance d, it is straightforward to have

$$\dot{z} = \mathrm{sech}^2(y)\dot{y} \tag{27}$$

After taking the time derivative of (8) and invoking (10) and the fact that $\dot{e} = \dot{q}$ for set-point control, it is clear that

$$\dot{y} = \eta \tag{28}$$

Again recalling the definition of z in (13) and the property of function, it is easy to have

$$\operatorname{atanh}(z + k_i^{-1} d) = \operatorname{atanh}(\tanh(y)) = y \tag{29}$$

In the light of (27)–(29), it is easy to conclude that

$$\operatorname{sech}^{-2}(a\tanh(z + k_i^{-1} d)) z\dot{z} = \operatorname{sech}^{-2}(y) z \operatorname{sech}^2(y)\eta = z\eta \tag{30}$$

Now substituting $J\dot{\eta}$ from (17) and (30) into (26), we have

$$\begin{aligned} \dot{V} &= -a_m \eta[\tanh(k_d \eta + \varphi(e)) - \tanh(\varphi(e))] \\ &\quad - \lambda a_m \tanh(\varphi(e))\tanh(e) - (b - \lambda J \operatorname{sech}^2(e))\dot{q}^2 \end{aligned} \tag{31}$$

By virtue of Lemma 1, it yields

$$-a_m \eta[\tanh(k_d \eta + \varphi(e)) - \tanh(\varphi(e))] \le 0 \tag{32}$$

Upon applying (32) to (31), the final upper bound for $\dot{V}$ is

$$\dot{V} \le -\lambda a_m \tanh(\varphi(e))\tanh(e) - (b - \lambda J)\dot{q}^2 \tag{33}$$

Obviously, $\dot{V} \le 0$ and $\dot{V} = 0$ implies that $e = 0$ and $\dot{q} = 0$. Hence, by invoking LaSalle's invariance principle (Slotine & Li, 1991), the globally asymptotic stability shown in Theorem 1 directly follows. This ends the proof.□

Remark 2. The proposed SPID control is constructed within the framework of saturated PID control methodology with very simple and intuitive structure and without reference to any modelling parameter, and thus it is easy to implement. The gains of the proposed SPID control can be tuned as follow: the positive constants α and δ to shape the error should be determined first. Normally, δ can be chosen as $\delta = 0.01$ for most motion systems and smaller α is helpful for faster transient but too small α may induce chattering. Then, k_i should be chosen to satisfy the condition (18) in Theorem 1 for disturbance rejection. After that, a_m can be chosen subject to constraint $a_m < u_{\max} - k_i$ from (19). Finally, k_p and k_d can be freely tuned following the abundant guidelines for PD control for motion systems.

Remark 3. On the basis of the above derivation, for the position control of motion systems (1), the commonly-used three-term saturated PID (cSPID) control maybe conceived as

$$u = -k_p \tanh(k_{p0} s(e)) - k_d \tanh(k_{d0}\dot{q}) - k_i \tanh(y) \tag{34}$$

where k_p, k_i, k_d, and y are the same as (7), and k_{p0} and k_{d0} are positive sharpness factors. It is easily to see that to avoid the actuator saturation, the control gains of the cSPID control should be chosen to satisfy

$$k_p + k_i + k_d < u_{\max} \tag{35}$$

Remark 4. Comparing (7) and (34), and (19) and (35), it is clear that the proposed SPID control has simple structure and it embeds the PD action within a single saturation function. Benefiting from this single saturation function embedment, the proposed SPID control removes the elaborated discrimination of proportional and derivative gains within the allowable actuator constraint and permits free choice and hence the further performance improvement is expected.

4. AN ILLUSTRATIVE EXAMPLE

In this section, the effectiveness and improved performance of the proposed SPID control is illustrated by an example used in (Cheng & Peng, 2007). The dynamics of the positioning system is given as (1) with $J = 0.1245\ \mathrm{N \cdot m \cdot rad^{-1} \cdot s^2}$ and $b = 0.3516\ \mathrm{Nm \cdot rad^{-1} \cdot s}$. The actuator constraint is $u_{\max} = 1\ \mathrm{Nm}$. Similar to (Cheng & Peng, 2007), the desired set-point is $q_d = 0.1\,\mathrm{rad}$ and the disturbance is $d = 0.05\,\mathrm{Nm}$. All other conditions are also the same as (Cheng & Peng, 2007). The CNF control is given as (Cheng & Peng, 2007, eqs. (2) and (50))

$$u = sat(u_0) = \operatorname{sign}(u_0)\min\{u_{\max}, |u_0|\} \tag{36}$$

$$u_0 = -F\begin{pmatrix} q \\ \dot{q} \end{pmatrix} + \frac{\omega^2}{b_1} q_d + \rho(e) F_n \begin{pmatrix} e \\ \dot{q} \end{pmatrix} - \hat{d} \tag{37}$$

where the matrices F and F_n, and function $\rho(e)$ are as

$$F = \left[\frac{\omega^2 + a_0}{b_1}, \frac{2\zeta\omega + a_1}{b_1}\right] \tag{38}$$

$$F_n = \left[\frac{\omega^2}{b_1}, \frac{(1+\varepsilon)\omega}{2\zeta b_1}\right] \tag{39}$$

$$\rho(e) = -\beta\left|\exp\left(-\gamma|e|\right) - \exp\left(-\gamma|q(0) - x_d|\right)\right| \tag{40}$$

and $\hat{d}$ is obtained by the following reduced-order observer (Cheng & Peng, 2007, eqs. (49))

$$\begin{cases} \dot{x}_v = A_v x_v + B_v sat(u_0) + C_v q \\ \hat{p} = x_v + L_v q \end{cases} \tag{41}$$

with $x_v = (x_{v1}, x_{v2})^T$ is the output of the observer, $\hat{p} = (\hat{x}_2, \hat{d})^T$ with $\hat{x}_2$ and $\hat{d}$ is the estimated velocity $\dot{q}$ and d, respectively, and matrices A_v, B_v, and L_v are defined as

$$A_v = \begin{bmatrix} -\sqrt{2}\omega_v & b_1 \\ -\omega_v^2/b_1 & 0 \end{bmatrix},\ B_v = \begin{bmatrix} b_1 \\ 0 \end{bmatrix} \tag{42}$$

$$C_v = \begin{bmatrix} a_0 - \sqrt{2}a_1\omega_v - \omega_0^2 \\ -(a_1\omega_v^2 + \sqrt{2}\omega_v^3)/b_1 \end{bmatrix},\ L_v = \begin{bmatrix} a_1 + \sqrt{2}\omega_v \\ \omega_v^2/b_1 \end{bmatrix} \tag{43}$$

where a_0, a_1, and b_1 are the system parameters obtained by J and b and are given as $a_0 = 0$, $a_1 = -2.825$, and $b_1 = 8.034$ (Cheng & Peng, 2007). Note that for a fair comparison we replace $\hat{x}_2$ with $\dot{q}$ in u_0 of (Cheng & Peng, 2007), due to the proposed control is full state feedback.

The control gains of the CNF are the same as (Cheng & Peng, 2007): $\zeta = 0.3$, $\omega = 6$, $\varepsilon = 0.1$, $\omega_v = 15$, $\gamma = 2$, and $\beta = 6$. The gains of the proposed SPID control are chosen as: $\delta = 0.01$, $\alpha = 0.5$, $\lambda = 0.5$, $a_m = 0.8$, $k_p = 40$, $k_i = 0.1$, and $k_d = 15$. The set-point error and requested control inputs are illustrated in Figs. 1 and 2, respectively.

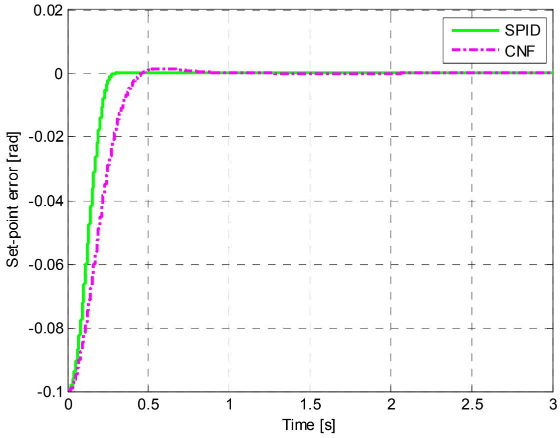

Fig. 1. Set-point error comparison with CNF control.

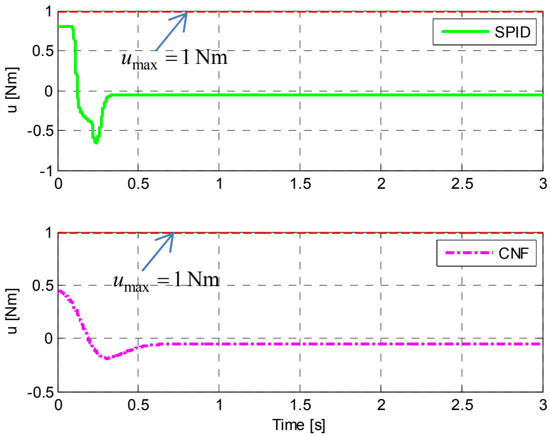

Fig. 2. Requested control inputs of SPID and CNF controls.

As we see, both two controls ensure that the positioning system completes the desired motion successfully and the set-point errors converge to zero asymptotically after a large initial errors. Obviously, the proposed SPID control obtains a much faster transient over the CNF control. The requested inputs of the two controls keep within the allowable level. Note that the faster transient of the SPID control is obtained with a quite simple and model-independent control.

After that, comparison with the commonly-used saturated PID (cSPID) control of (34). The conditions and gains of the SPID control are unchanged. The gains of the cSPID control are $k_p = 0.5$, $k_d = 0.48$, $k_{p0} = 35$, $k_{d0} = 30$, and the others are the same as SPID control. The results are shown in Figs. 3 and 4. Obviously, the proposed SPID control also gives a much faster transient over the cSPID control. Note that this favourable is benefitted from the complete embedment of the PD action within a single saturation function such that the proportional and derivative gains can be freely chosen. Although the sharpness factors k_{p0} and k_{d0} of the cSPID control can be freely chosen, but they are not directly formulated to the control action. Limited by the actuator constraint, the proportional and derivative gains k_p and k_d of the cSPID control cannot be chosen so large and hence the cSPID control cannot give a faster transient.

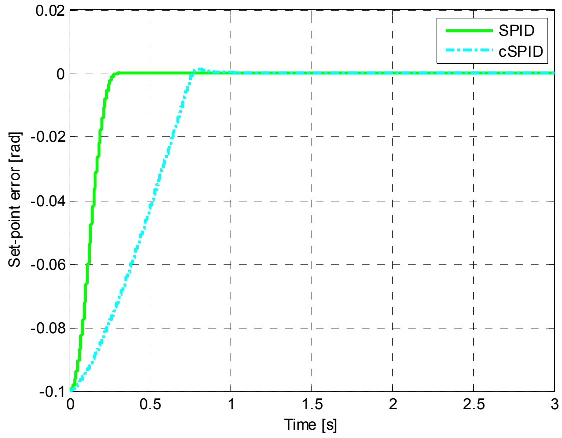

Fig. 3. Set-point error comparison with cSPID control.

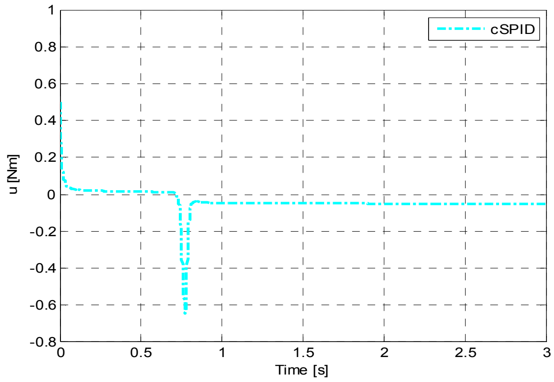

Fig. 4. Requested control input of cSPID control.

Finally, we show the benefit from the nonlinear function $s(e)$ by comparing with the following saturated linear PID (SLPID) control

$$u = -a_m \tanh(k_p e + k_d \dot{q}) - k_i \tanh(y) \tag{44}$$

where k_p, k_i, k_d, a_m, and y are the same as (7) and (8).

The gains of the SLPID control are the same as SPID control except $k_p = 100$ and $k_d = 70$. The results are shown in Figs. 5 and 6. It is clearly seen that the proposed SPID control achieves a much significant faster over the SLPID control.

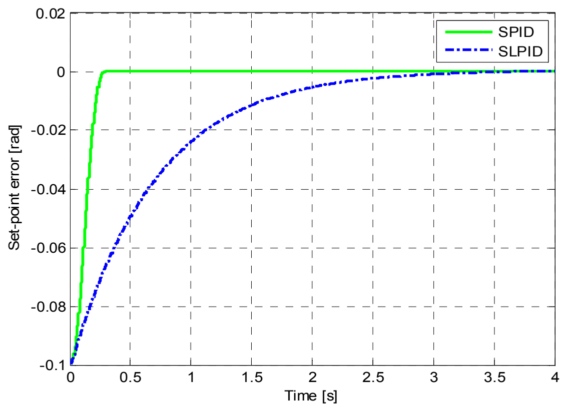

Fig. 5. Set-point error comparison with SLPID control.

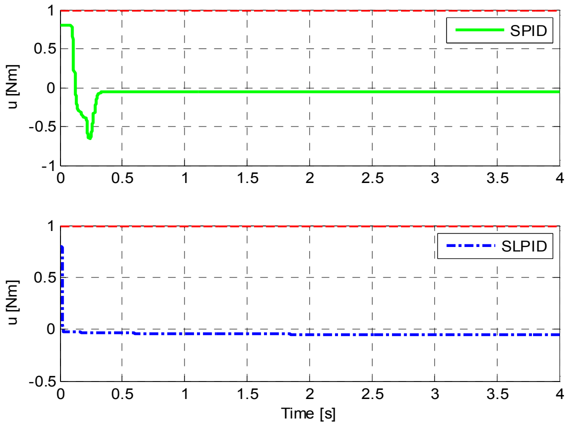

Fig. 6. Requested control inputs of SPID and SLPID controls.

On the basis of the above simulations, we can conclude that the proposed model-free SPID control provides a much improved solution for set-point control of uncertain motion systems with actuator constraint and constant disturbance.

5. CONCLUSIONS

In this paper, a simple but quite effective model-free saturated PID control is proposed for faster transient of motion systems subject to actuator constraint. The proposed controller consists of a saturated PD action and a saturated integral action for compensation of constant and slow time-varying bounded disturbances. Global asymptotic set-point stability is proven. The conditions ensuring global asymptotic stability and avoidance of actuator saturation are obtained. The improved performance of the proposed approach is demonstrated by a servo system. The proposed controller provides an easy-going solution for faster transient of uncertain motion systems subject to actuator constraint.

REFERENCES

Aangenent, W. H. T. M., Witvoet, G., Heemels, W. P. M. H., van de Molengraft, M. J. G., & Steinbuch, M. (2010). Performance analysis of reset control systems. *International Journal of Robust and Nonlinear Control*, 20(11), 1213–1233.

Armstrong, B. S. R., Guitierrez, J. A., Wade, B. A., & Joseph, R. (2006). Stability of phase-based gain modulation with designer-chosen switch functions. *International Journal of Robotics Research*, 25, 781–796.

Beerens, R., Bisoffi, A., Zaccarian, L., Heemels, W. P. M. H., Nijmeijer, H., & van de Wouw, N. (2019). Reset integral control for improved settling of PID-based motion systems with friction, *Automatica*, 107, 483–492

Beerens, R., Nijmeijer, H., Heemels, W. P. M. H., & van de Wouw, N. (2017). Set-point control of motion systems with uncertain set-valued Stribeck friction. *IFAC Papers Online*, 50(1), 2965–2970.

Bisoffi, A., Da Lio, M., Teel, A. R., & Zaccarian, L. (2018). Global asymptotic stability of a PID control system with Coulomb friction. *IEEE Transactions on Automation Control*, 63(8), 2654–2661.

Bucci, B. A., Cole, D. G., Ludwick, S. J., & Vipperman, J. S. (2013). Nonlinear control algorithm for improving settling time in systems with friction, *IEEE Transactions on Control Systems Technology*, 21(4), 1365–1374

Chen, B. M., Lee, T. H., Peng, K., & Venkataramanan, V. (2003). Composite nonlinear feedback control for linear systems with input saturation: Theory and an application, *IEEE Transactions on Automation Control*, 48(3), 427–439.

Cheng, G., & Peng, K. (2007). Robust composite nonlinear feedback control with application to a servo positioning system, *IEEE Transactions on Industrial Electronics*, 54(2), 1132–1140.

Cheng, G., & Hu, J. G. (2014). Robust proximate time-optimal servomechanism with speed constraint for rapid motion control, *Robotics and Computer-Integrated Manufacture*, 30(4), 379–388.

Galeani, S., & Teel, A. R. (2006). On a performance-robustness trade-off intrinsic to the natural anti-windup problem, *Automatica*, 42(11), 1849–1861.

Gayaka, S., Lu, L., & Yao, B. (2012). Global stabilization of a chain of integrators with input saturation and disturbances: A new approach. *Automatica*, 48(7), 1389–1396.

Hu, T., & Lin, Z. (2001). *Control Systems with Actuator Saturation: Analysis and Design*. Boston, MA: Birkhauser.

Hunnekens, B. G. B., van de Wouw, N., Heertjes, M. F., & Nijmeijer, H. (2015). Synthesis of variable gain integral controllers for linear motion systems. *IEEE Transactions on Control Systems Technology*, 23(1), 139–149.

van Loon, S. J. L. M., Hunnekens, B. G. B., Heemels, W. P. M. H., van de Wouw, N., & Nijmeijer, H. (2016). Split-path nonlinear integral control for transient performance improvement. *Automatica*, 66, 262–270.

Ohnishi, K., Shibata, M., & Murakami, T (1996). Motion control for advanced mechatronics, *IEEE/ASME Transactions on Mechatronics*, 1(1), 56–67.

Orlov, Y., Santiesteban, R., & Aguilar, L. T. (2009). Impulsive control of a mechanical oscillator with friction. In *Proceedings of American Control Conference* (pp.3494–3499).

Peng, K., Chen, B. M., Cheng, G., & Lee, T. H. (2005). Modeling and compensation of nonlinearities and friction in a micro hard disk drive servo system with nonlinear feedback control. *IEEE Transactions on Control Systems Technology*, 13(5), 708–721.

Putra, D., Nijmeijer, H., & van de Wouw, N. (2007). Analysis of undercompensation and overcompensation of friction in 1DOF mechanical systems. *Automatica*, 43(8), 1387–1394.

Salton, A. T., Al-Ghanimi, A., Flores, J. V., Zheng, J. C., Gomes da Silva, J. M., & Fu, M. (2017). Saturation-aware control design for micro–nano positioning systems. *IET Control Theory and Applications*, 11(15), 2559–2566.

Salton, A. T., Chen, Z., & Fu, M. (2012). Improved control design methods for proximate time-optimal servomechanisms. *IEEE/ASME Transactions on Mechatronics*, 17(6), 1049–1058.

Slotine, J. J. E., & Li, W. (1991). *Applied Nonlinear Control*. Prentice Hall, NJ: Englewood Cliffs.

Su, Y. X., Müller, P. C., & Zheng, C. H. (2010). Global asymptotic saturated PID control for robot manipulators. *IEEE Transactions on Control Systems Technology*, 18(6), 1280–1288.

Su, Y. X., Zheng, C. H., & Mercorelli, P. (2017). Global finite-time stabilization of planar linear systems with actuator saturation. *IEEE Transactions on Circuits and Systems–II: Express Briefs*, 64(8), 947–951.

Workman, M. (1987). Adaptive proximate time-optimal control servomechanisms, Ph.D. dissertation, Stanford University.

van de Wouw, N., & Leine, R. I. (2012). Robust impulsive control of motion systems with uncertain friction. *International Journal of Robust and Nonlinear Control*, 22, 369–397.

van de Wouw, N., Pastink, H. A., Heertjes, M. F., Pavlov, A. V., & Nijmeijer, H. (2008). Performance of convergence-based variable-gain control of optical storage drives. *Automatica*, 44(1), 15–27.

Zheng, C. H., Su, Y. X., & Mercorelli, P. (2018). Simple relay non-linear PD control for faster and high-precision motion systems with friction. *IET Control Theory and Applications*, 12(17), 2302–2308.

Zheng, C. H., Su, Y. X., & Mercorelli, P. (2019a). A simple nonlinear PD control for faster and high-precision positioning of servomechanisms with actuator saturation. *Mechanical Systems and Signal Processing*, 121, 215–226.

Zheng, C. H., Su, Y. X., & Mercorelli, P. (2019b). Faster positioning of one degree-of-freedom mechanical systems with friction and actuator saturation. *Journal of Dynamic Systems, Measurement, and Control*, 141(6), 064504.

Zheng, C. H., Su, Y. X., & Mercorelli, P. (2019c) Simple saturated relay non-linear PD control for uncertain motion systems with friction and actuator constraint. *IET Control Theory and Applications*, 13(12), 1920–1928.