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Article

An Adaptive Real-Time Third Order Sliding Mode Control for Nonlinear Systems

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Abstract: As most real world systems are significantly nonlinear in nature, developing robust controllers have attracted many researchers for decades. Robust controllers are the controllers that are able to cope with the inherent uncertainties of the nonlinear systems. Many control methods have been developed for this purpose. Sliding mode control (SMC) is one of the most commonly used methods in developing robust controllers. This paper presents a higher order SMC (HOSMC) approach to mitigate the chattering problem of the traditional SMC techniques. The developed approach combines a third order SMC with an adaptive PID (proportional, integral, derivative) sliding surface to overcome the drawbacks of using PID controller alone. Moreover, the presented approach is capable of adaptively tuning the controller parameters online to best fit the real time applications. The Lyapunov theory is used to validate the stability of the presented approach and its feasibility is tested through a comparison with other conventional SMC approaches.

Keywords: SMC; uncertain nonlinear systems; PID; lyapunov theory

1 Introduction

Nonlinear control covers a wide range of systems that exist in many real world applications. These applications include robot control [1], satellite control [2], and spacecraft control [3]. These nonlinear systems are often modeled by nonlinear differential equations. Several rigorous techniques have been developed to handle these systems. Examples of these techniques are feedback linearization control (FLC) [4], back-stepping control (BSC) [5], intelligent control (e.g., neural networks, and fuzzy logic) [6,7], adaptive control [6,7], and SMC [1,8]. Each technique can be applied to certain systems and characteristics. Thus, there is no general solution for all types of nonlinear control systems.

Generally, feedback linearization is the one of the most attractive techniques used to tackle nonlinear systems as it is based on transforming nonlinear systems into simpler forms. However, this technique does not provide efficient solutions for significant nonlinear systems which have high nonlinearities and uncertainties. Backstepping control (BSC) is also one of the most popular techniques used to control higher order systems. Nevertheless, the main disadvantage of BSC is the requirement of exact system model which cannot be guaranteed for nonlinear systems with inherent uncertainties. Thus, adaptive control is combined with BSC to mitigate the requirement of exact model. On the other hand, SMC shows great capabilities of dealing with nonlinearity and uncertainties [9–11]. The more the degree of nonlinearity and uncertainty, the more need to design robust controllers for control systems.

Tackling uncertain nonlinear systems is very challenging especially for real time control systems [12]. Uncertainties occur mainly due to un-modeled high frequency dynamics, and neglected nonlinearities [13]. These uncertainties usually affect the system performance, and stability [14]. Accordingly, many researchers have been working towards developing robust controllers that are able to mitigate these uncertainties [15–17]. Among many developed solutions, SMC is one of the most popular and effective solutions that can cope with significant uncertainties, and parameters' variations [9–11]. Moreover, SMC technique shows a strong capability to compensate for external perturbations.

As SMC techniques are very efficient in dealing with significant uncertainties, and nonlinearities, they have been widely used for decades especially for nonlinear control applications [18,19]. The first order SMC is the simplest structure used in the literature to cope with uncertainties and external disturbances [20]. Although, the conventional (first order) SMC presents a good solution for uncertainties compensation in the control system design process, it is suitable only for systems with output of degree of one. Furthermore, it suffers from the chattering problem which sometimes degrades the system performance, and affects the system stability. Thus, many attempts have been seen to replace the conventional SMC with higher order SMC (HOSMC) techniques that are suitable for higher order systems and able to attenuate the chattering occurred with conventional SMC. Super-twisting SMC (STSMC) is one popular extension of the conventional SMC [21]. The STSMC is a second order structure of SMC that is able to reduce the oscillations that occurs around the sliding surface during the switching control phase of the SMC. The main power of STSMC is that it does not require the implementation of the derivative of the sliding variable which is the main challenge of other HOSMC techniques [22–24]. Nevertheless, STSMC design process requires the accurate setting of many control gains as it affects the performance and stability of the control system. This is a very challenging process. Accordingly, many STSMC techniques have been developed to tackle this challenge such as adaptive STSMC [25], adaptive dual layer STSMC [26], and integral STSMC [27].

Ensuing in the same path, this paper presents a new HOSMC approach that is able to overcome the chattering problem occurred in the conventional SMC. The developed approach uses a third order SMC combined with an adaptive PID sliding surface. This combined approach overcomes the drawbacks of using PID controller alone. Furthermore, the presented approach is capable of adaptively tuning the controller parameters online which is perfectly fit with real time applications. By the combination of adaptive control with the SMC, the developed approach allows of the relaxation of the boundness condition of uncertainty level. The proposed approach shows a better performance than other SMC approaches in terms of chattering attenuation, and tracking error. The stability of the developed control approach is validated through Lyapunov theory. The main contributions of this work can be summarized as follows:

[1] Presenting a real time third order SMC approach for nonlinear systems able to mitigate the chattering problem associated with other conventional SMC approaches. The proposed approach is capable of achieving excellent performance even with the existence of all types of uncertainties and disturbances. The proposed approach is capable of estimating uncertainties and thus no worries about the upper bound problem associated with working with uncertainties.

[2] An adaptive PID tuning algorithm is presented to reach the optimal estimation of PID controller parameters which are adaptively changing during the online control process.
[3] A quadratic Lyapunov function is suggested and used to validate the proposed approach stability considering the estimated uncertainties. The developed control law guarantees that the system will reach the sliding surface in a finite time.

The rest of this paper is organized as follows. Section 2 presents the proposed adaptive third order SMC approach. Some simulations are introduced in Section 3. Conclusions and some future directions are drawn in Section 4.

2 The Proposed Approach

The proposed Adaptive Real Time PID-based Third Order SMC (APID-TOSMC) is vindicated in this section.

A controlled system can be modeled as [19,28]:

$$\begin{aligned} \ddot{x}(t) &= F(z(t), t) + G(z(t), t)\, r(t) + \gamma(t) \\ x(t) &= z_1(t) \end{aligned} \tag{1}$$

where $r(t)$ is the control input of the system, $z(t) = \left[x \ \dot{x} \ \ddot{x} \ldots\ldots \overset{(n-1)}{x}\right]^T$ is the system state variables, and $x(t)$ is the measured response of the system. $F(z(t), t)$ and $G(z(t), t)$ are uncertain nonlinear functions. The unknown uncertainties are represented by $\gamma(t)$ with an upper bound given by $B \le |\gamma(t)|$. The dynamical model of the controlled system (Eq. (1)) is modified to include uncertainties as follows:

$$\begin{aligned} \ddot{x}(t) &= F_n(z(t), t) + \Delta F(z(t), t) + (G_n(z(t), t) + \Delta G(z(t), t))\ r(t) + \gamma(t) \\ \ddot{x}(t) &= F_n(z(t), t) + G_n(z(t), t)\, r(t) + \mu(t) \end{aligned} \tag{2}$$

where $F_n(z(t), t)$ and $G_n(z(t), t)$ are the nominal values of $F(z(t), t)$ and $G(z(t), t)$, respectively. The parameter variations (uncertainties) are represented by $\Delta F(z(t), t)$ and $\Delta G(z(t), t)$.

The lumped uncertainty is defined as:

$$\mu(t) = \Delta F(z(t), t) + \Delta G(z(t), t)\, r(t) + \gamma(t) \tag{3}$$

The switching surface for the APID-TOSMC can be demarcated as:

$$\sigma(t) = \ddot{s}(t) + \beta_2 \dot{s}(t) + \beta_1 s(t) = \hat{k}_d \dot{e}(t) + \hat{k}_p e(t) + \hat{k}_i \int e(\xi) d\xi \tag{4}$$

The addressed problem in this paper is to design an adaptive online Tuned PID-based APID-TOSMC for nonlinear systems such that the system response $x(t)$ strongly follows a reference desired signal $x_d(t)$.

The control effort of APID-TOSMC is designed as:

$$r(t) = r_{eq}(t) + r_s(t) \tag{5}$$

where $r_{eq}(t)$ and $r_s(t)$ are the equivalent and reaching control efforts respectively.

The third derivative of $s(t)$ can be deduced from Eq. (4):

$$\dddot{s}(t) = -\beta_1 \dot{s}(t) - \beta_2 \ddot{s}(t) + \hat{k}_d \ddot{e}(t) + \hat{k}_p \dot{e}(t) + \hat{k}_i e(t) \tag{6}$$

Substituting $\left(\ddot{e}(t) = \ddot{x}(t) - \ddot{x}_d(t)\right)$ into Eq. (6) and considering Eq. (2), we get:

$$\dddot{s}(t) = -\beta_1 \dot{s}(t) - \beta_2 \ddot{s}(t) + \hat{k}_d F_n + \hat{k}_d G_n r(t) + \hat{k}_d \mu(t) - \hat{k}_d \ddot{x}_d(t) + \hat{k}_p \dot{e}(t) + \hat{k}_i e(t) \tag{7}$$

The equivalent control effort $\left(r_{eq}(t)\right)$ is calculated by setting $\dddot{s}(t) = 0$, and $(\mu(t) = 0)$:

$$r_{eq}(t) = \frac{1}{\hat{k}_d G_n} \left\{\beta_1 \dot{s}(t) + \beta_2 \ddot{s}(t) - \hat{k}_d F_n + \hat{k}_d \ddot{x}_d(t) - \hat{k}_p \dot{e}(t) - \hat{k}_i e(t)\right\} \tag{8}$$

To prove the system stability, a Lyapunov function is chosen as:

$$V(t) = \frac{1}{2} \ddot{s}^2(t) + \frac{k_2}{2} \dot{s}^2(t) + \frac{k_1}{2} s^2(t) + \frac{1}{2\gamma_d} \tilde{k}_d^2 + \frac{1}{2\gamma_p} \tilde{k}_p^2 + \frac{1}{2\gamma_i} \tilde{k}_i^2 \tag{9}$$

where k_1, k_2 are constants (design parameters).

The derivative of Lyapunov function $\dot{V}(t)$ is:

$$\dot{V}(t) = \ddot{s}(t) \; \dddot{s}(t) + k_1 s(t) \; \dot{s}(t) + k_2 \dot{s}(t) \; \ddot{s}(t) + \frac{1}{\gamma_p} \tilde{k}_p \dot{\tilde{k}}_p + \frac{1}{\gamma_d} \tilde{k}_d \dot{\tilde{k}}_d + \frac{1}{\gamma_i} \tilde{k}_i \dot{\tilde{k}}_i \tag{10}$$

Substituting for $\dddot{s}$ from Eq. (7) into Eq. (10) yields:

$$\begin{aligned}\dot{V}(t) &= k_2 \dot{s}(t) \; \ddot{s}(t) + k_1 s(t) \; \dot{s}(t) + \ddot{s}(t) \{-\beta_1 \dot{s}(t) - \beta_2 \ddot{s}(t) + \hat{k}_d F_n + \hat{k}_d \mu(t) + \hat{k}_i e(t) \\ &+ \hat{k}_d G_n (r(t)) - \hat{k}_d \ddot{x}_d(t) + \hat{k}_p \dot{e}(t)\} + \tfrac{1}{\gamma_p} \tilde{k}_p \dot{\tilde{k}}_p + \tfrac{1}{\gamma_d} \tilde{k}_d \dot{\tilde{k}}_d + \tfrac{1}{\gamma_i} \tilde{k}_i \dot{\tilde{k}}_i\end{aligned} \tag{11}$$

$$\begin{aligned}\dot{V}(t) &= k_2 \dot{s}(t) \; \ddot{s}(t) + k_1 s(t) \; \dot{s}(t) + \ddot{s}(t) \{-\beta_1 \dot{s}(t) - \beta_2 \ddot{s}(t) + \hat{k}_d F_n + \hat{k}_d \mu(t) + \hat{k}_i e(t) \\ &+ \hat{k}_d G_n \left(r_{eq}(t) + r_s(t)\right) - \hat{k}_d \ddot{x}_d(t) + \hat{k}_p \dot{e}(t)\} + \tfrac{1}{\gamma_p} \tilde{k}_p \dot{\tilde{k}}_p + \tfrac{1}{\gamma_d} \tilde{k}_d \dot{\tilde{k}}_d + \tfrac{1}{\gamma_i} \tilde{k}_i \dot{\tilde{k}}_i\end{aligned} \tag{12}$$

Using Eqs. (8) and (12) becomes:

$$\begin{aligned}\dot{V}(t) &= k_2 \dot{s}(t) \; \ddot{s}(t) + k_1 s(t) \; \dot{s}(t) + \ddot{s}(t) \left\{ \hat{k}_d G_n r_s(t) + \hat{k}_d \mu(t)\right\} + \frac{1}{\gamma_p} \tilde{k}_p \dot{\tilde{k}}_p \\ &+ \tfrac{1}{\gamma_d} \tilde{k}_d \dot{\tilde{k}}_d + \tfrac{1}{\gamma_i} \tilde{k}_i \dot{\tilde{k}}_i\end{aligned} \tag{13}$$

The switching control effort $r_s(t)$ can be chosen as:

$$\begin{aligned}r_s(t) = \frac{-1}{\hat{k}_d G_n} &\{k_2 \dot{s}(t) + k_3 sign(\ddot{s}(t)) + \ddot{s}(t) \left(\hat{k}_d \dot{e}(t) + \hat{k}_p e(t) + \hat{k}_i \textstyle\int e(\xi) d\xi\right) \\ &+ \tfrac{k_1 \dot{s}(t) \; s(t)}{\ddot{s}(t) - \varepsilon}\}\end{aligned} \tag{14}$$

where the switching control gain k_3 is a design parameter and ε is a very small positive number.

$$\begin{aligned}\dot{V}(t) &= -k_2 \ddot{s}(t)\, s(t) \; - \ddot{s}(t)\frac{k_1 \dot{s}(t)\; s(t)}{\ddot{s}(t) - \varepsilon} - \ddot{s}^2(t)\left(\hat{k}_d\, \dot{e}(t) + \hat{k}_p\, e(t) + \hat{k}_i \int e(\xi)d\xi\right) \\ &- k_3 \ddot{s}(t) sign\left(\ddot{s}(t)\right) + \ddot{s}(t)\hat{k}_d\mu(t) + k_1 s(t)\, \dot{s}(t) + k_2 \ddot{s}(t)\, \dot{s}(t) + \tfrac{1}{\gamma_p}(\hat{k}_p - k_p)\dot{\hat{k}}_p \\ &+ \tfrac{1}{\gamma_d}(\hat{k}_d - k_d)\dot{\hat{k}}_d + \tfrac{1}{\gamma_i}(\hat{k}_i - k_i)\dot{\hat{k}}_i\end{aligned} \tag{15}$$

For $\dot{V}(t) < 0$, the adaptive algorithm laws can be chosen as:

$$\begin{aligned}\dot{\hat{k}}_p &= \gamma_p\, e(t)\, \ddot{s}^2(t) \\ \dot{\hat{k}}_i &= \gamma_i\, \ddot{s}^2(t)\, \int e(\xi)d\xi \\ \dot{\hat{k}}_d &= \gamma_d\, \dot{e}(t)\, \ddot{s}^2(t)\end{aligned} \tag{16}$$

Substituting from Eq. (16) into Eq. (15) and eliminating similar terms yields:

$$\dot{V}(t) = -\ddot{s}^2(t)\left(k_d\, \dot{e}(t) + k_p\, e(t) + k_i \int e(\xi)d\xi\right) - k_3 \ddot{s}(t) sign\left(\ddot{s}(t)\right) + \ddot{s}(t)\hat{k}_d\mu(t) \tag{17}$$

By using $\left|\dot{s}(t)\right| = \dot{s}(t) sign\left(\dot{s}(t)\right)$, Eq. (17) becomes:

$$\begin{aligned}\dot{V}(t) &= -k_3 \left|\ddot{s}(t)\right| + \hat{k}_d\mu(t)\, \ddot{s}(t) - \ddot{s}^2(t)\left(k_d\, \dot{e}(t) + k_p\, e(t) + k_i \int e(\xi)d\xi\right) \\ \dot{V}(t) &\le -\left|\ddot{s}(t)\right| \{k_3 - \hat{k}_d\, |\mu(t)|\} - \ddot{s}^2(t)\left(k_d \left|\dot{e}(t)\right| + k_p\, |e(t)| + k_i \int |e(\xi)|\, d\xi\right)\end{aligned} \tag{18}$$

The switching gain k_3 must be set as $\left(k_3 > \hat{k}_d\, |\mu(t)|\right)$ for global stability. The schematic diagram of the adopted APID-TOSMC controller is shown in Fig. 1.

3 Simulations and Discussions

With the aim to assess the performance of (APID-TOSMC) approach, some simulations are done using Matlab software considering the stabilization of the inverted pendulum system. Different types of uncertainties are considered. Two problems are assessed; setpoint control and path following control.

3.1 Setpoint Control

The developed APID-TOSMC approach in this paper is analyzed in comparison with the second order SMC approach in [28] and the adaptive third order SMC (ATOSMC) approach in [29]. The simulation parameters and conditions are set exactly as in [28] and the algorithm in [29] is implemented with same parameters and conditions. The desired angular position is set as: $\theta_d = 0$ with initial conditions $Y_0 = [\frac{\pi}{8}, 0]$. In order to examine the robustness of the controller, two cases of uncertainties are considered: the external perturbations $(\rho(t) = \left(1 + \sin(\frac{\pi}{2}t)\right))$ and the abrupt perturbations (a $1000N$ force is abruptly applied at the pole at $t = 2.5$ sec). The proposed APID-TOSMC parameters are set as: $\beta_2 = 0.005$, $k_3 = 50$, $k_1 = 1$, $\beta_1 = 0.008$, $\gamma_p = 1.1$, $\gamma_i = 0.06$, $\gamma_d = 0.036$ and $k_2 = 1$. The angular position (θ) of the proposed APID-TOSMC approach compared with the approaches in [28,29] is shown in Fig. 2. Furthermore, Fig. 3 shows the angular position error of the three approaches.

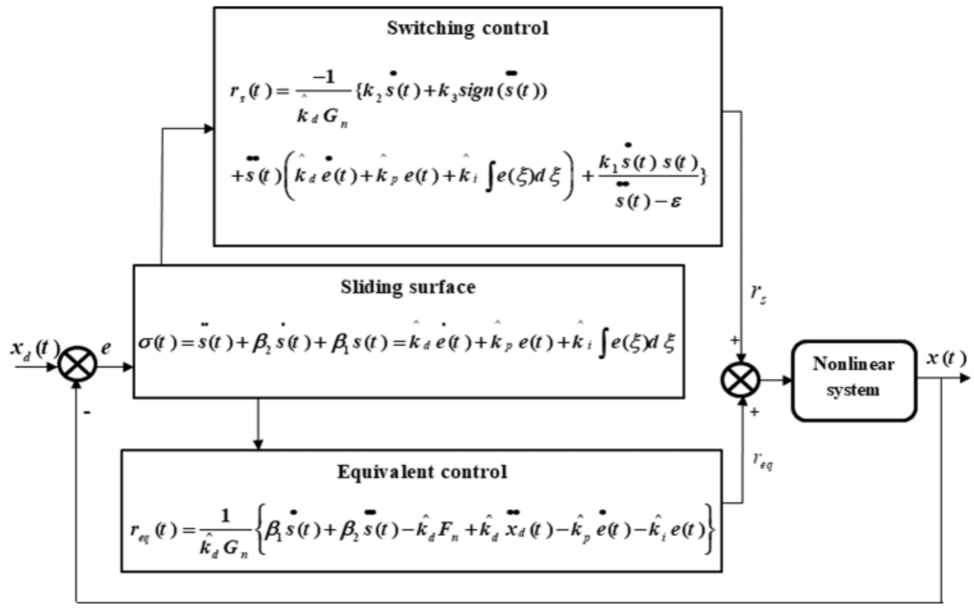

Figure 1: Schematic diagram of the adopted APID-TOSMC controller

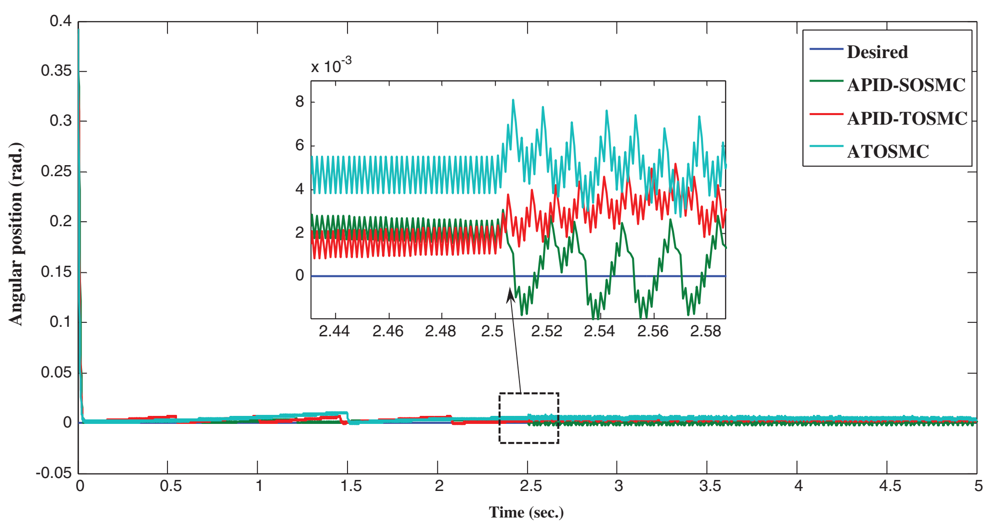

Figure 2: Angular position (θ) response

Figs. 2 and 3 illustrate that the APID-TOSMC controller can achieve favorable and satisfied trajectory tracking control performance. Additionally, the proposed APID-TOSMC control methodology is able to perfectly control the inverted pendulum. The results show the developed controller is very robust even in the existence of external perturbations and uncertainties compared to other approaches.

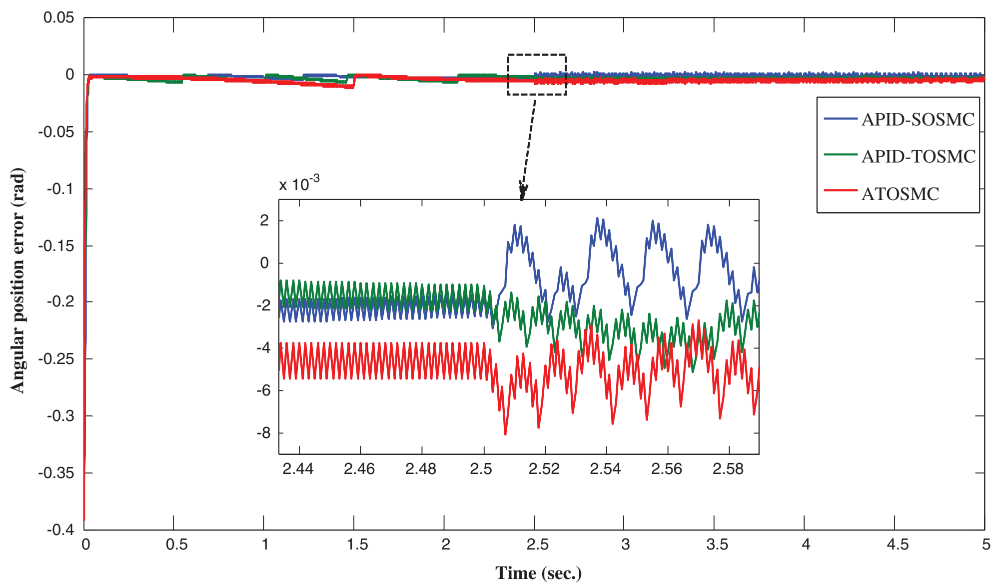

Figure 3: Angular position error response

Figs. 4–6 show the adaptive PID sliding surface values for the set point tracking control of APID-TOSMC controller.

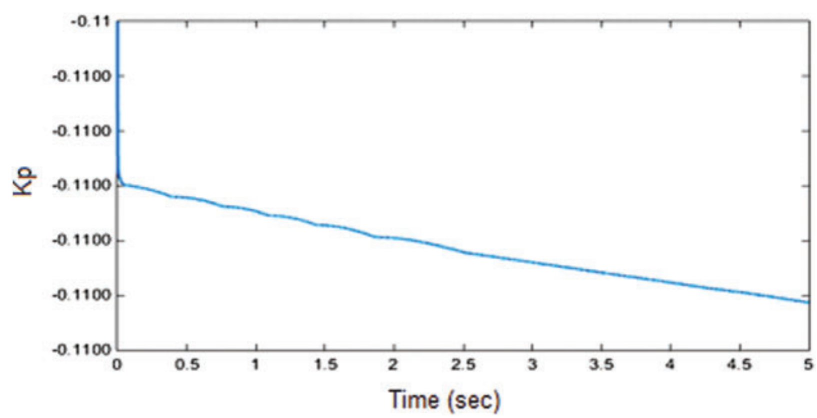

Figure 4: The adaptive value of the proportional parameter of APID-TOSMC for set point control

To more evaluate the developed approach, three parameters are used; integral absolute error (IAE), integral time absolute error (ITAE), and integral of squared error. Tab. 1 shows the obtained results of our approach is excellent compared with the approach proposed in [28] and has a better performance than the approach in [29].

Also, Fig. 7 shows a comparison between the control signal of the presented APID-TOSMC approach and the approach proposed in [28,29]. As shown, the control signal for our proposed approach has less chattering than the other approaches.

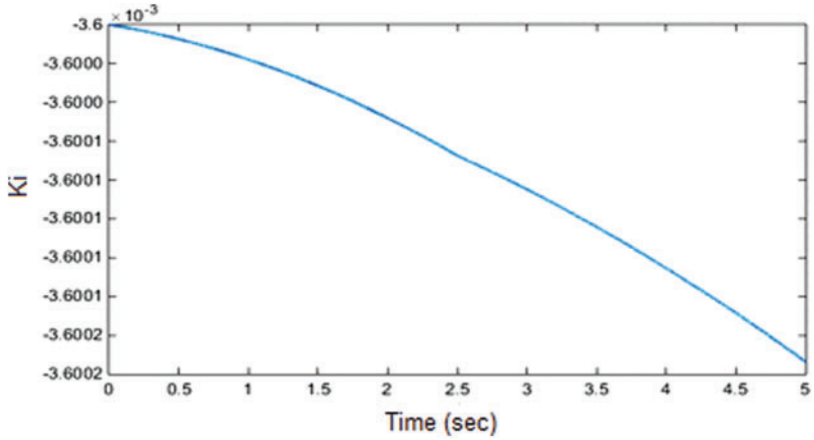

Figure 5: The adaptive value of the integrator parameter of APID-TOSMC for set point control

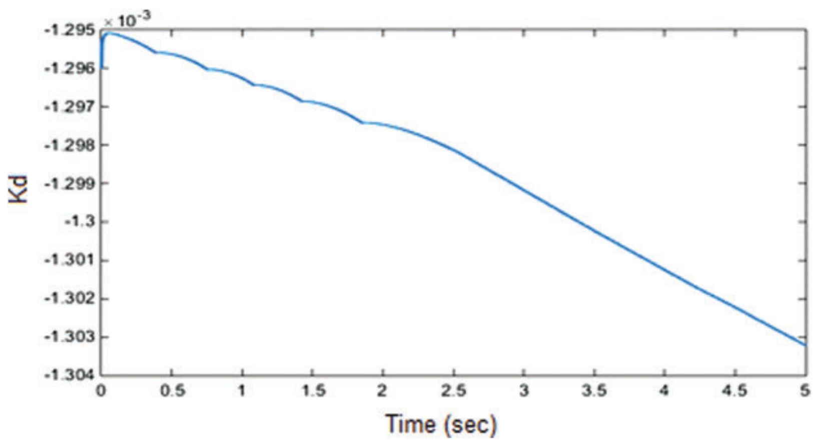

Figure 6: The adaptive value of the differentiator parameter of APID-TOSMC for set point control

Table 1: Performance comparison for set point control problem

Approach	IAE	ITAE	ISE
APID-SOSMC	20.8461	47.0039	1.2669
APID-TOSMC	15.1146	20.6926	1.1023
ATOSMC	15.9854	21.3514	1.2016

3.2 Path Following Control

The second case of control to consider in this section is the trajectory tracking control of the inverted pendulum. Again, the simulation parameters and conditions are set exactly as in [28] and the algorithm in [29] is implemented with same parameters and conditions. The external perturbation is set to: $\rho(t) = (0.2\sin(0.25t))$ with initial conditions $Y_0 = [\frac{\pi}{6}, 0]$ [27]. The proposed APID-TOSMC parameters are set as: $\beta_2 = 0.005, \beta_2 = 0.005$, $k_3 = 50$, $k_1 = 1$, $\beta_1 = 0.008$, $\gamma_p = 1.1$, $\gamma_i = 0.06$, $\gamma_d = 0.036$ and $k_2 = 1$. To test the robustness of the presented APID-TOSMC approach, a 1000 N force is abruptly applied at the pole at $t = 5$ sec. The control and error responses are illustrated in Figs. 8 and 9 respectively.

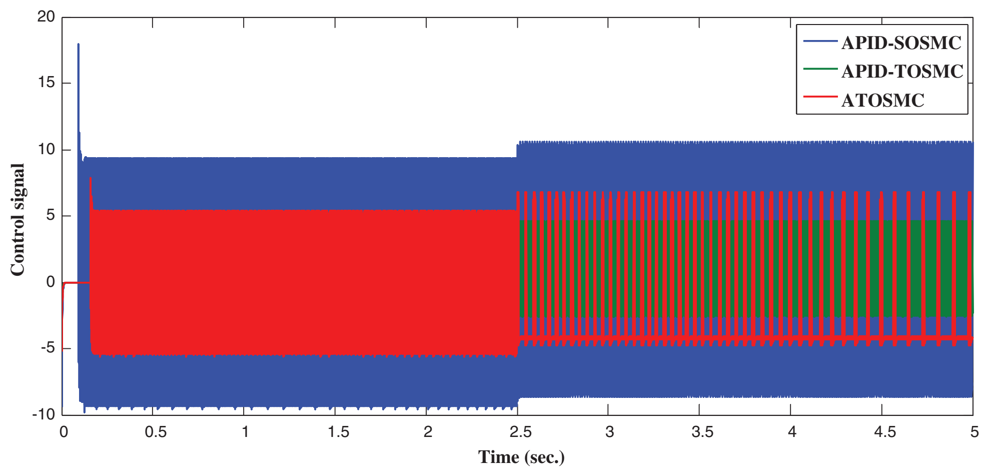

Figure 7: The total control signal for set point control

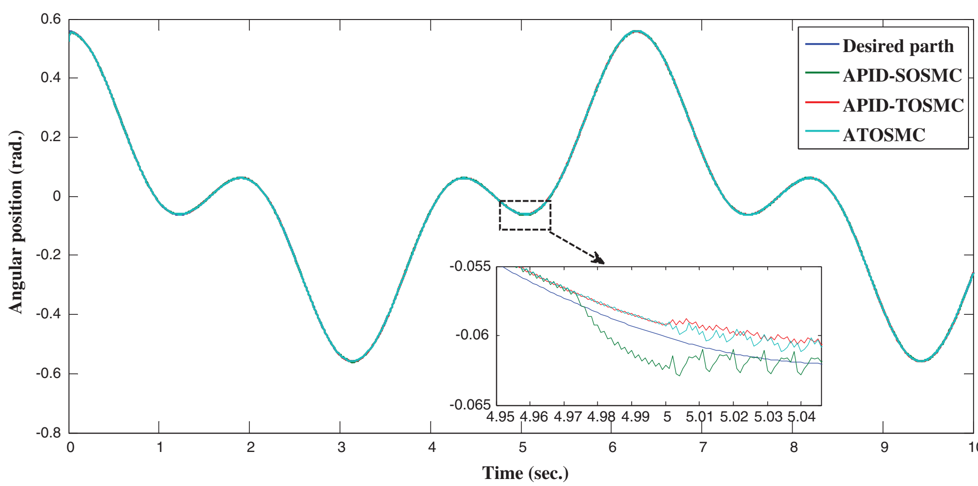

Figure 8: Angular position (θ)

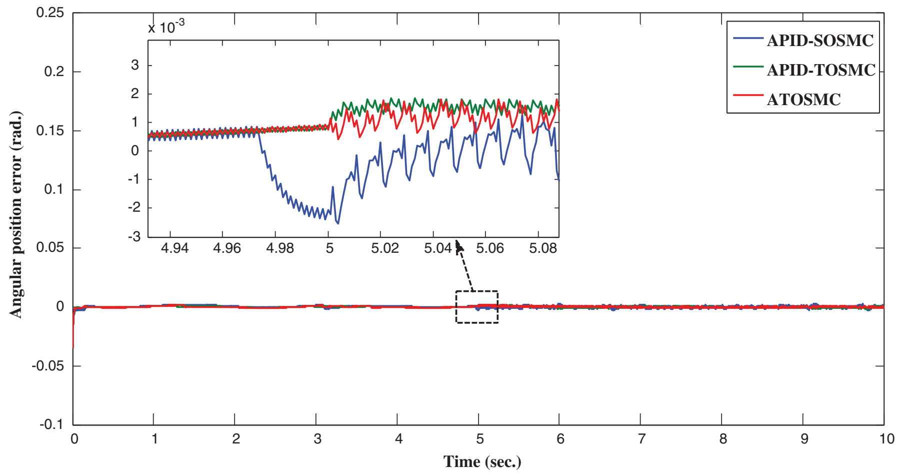

Figure 9: Angular position error

Figs. 10–12 show how the PID sliding surface values are adaptively changing over time.

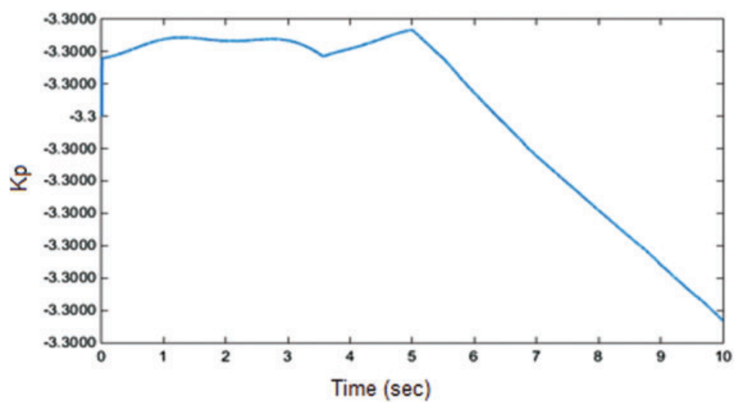

Figure 10: The adaptive value of the proportional parameter of APID-TOSMC for path following control

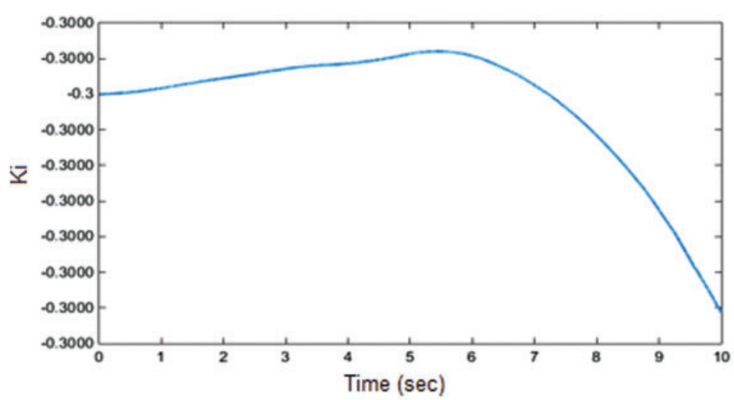

Figure 11: The adaptive value of the integrator parameter of APID-TOSMC for path following control

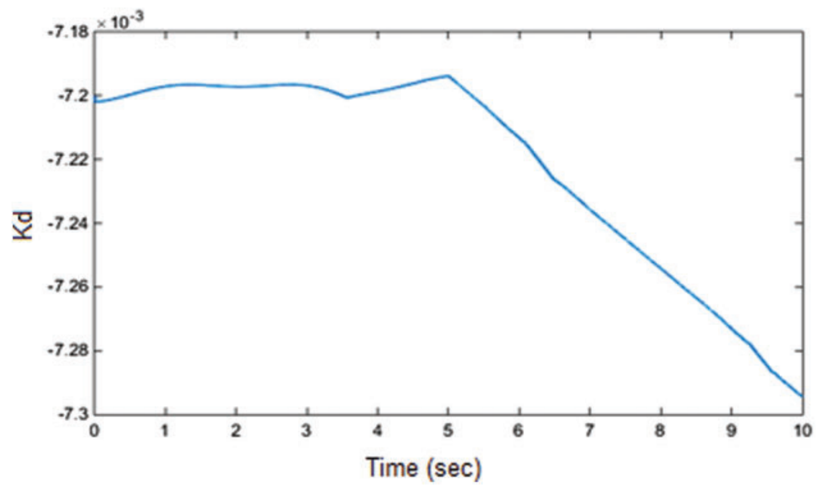

Figure 12: The adaptive value of the differentiator parameter of APID-TOSMC for path following control

Fig. 13 demonstrates the control signals of the APID-SOSMC and APID-TOSMC approaches.

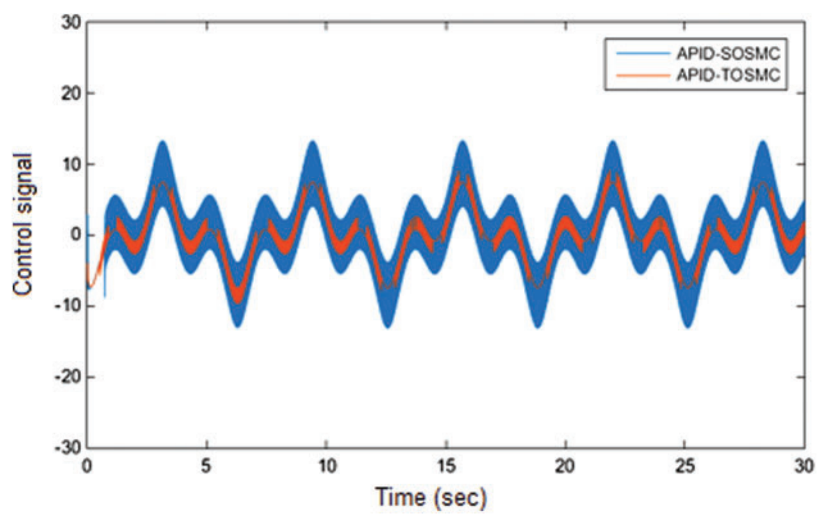

Figure 13: The control signal for path following control

It has been shown in this section that the developed controller (APID-TOSMC) attained better path following response than the controllers in [28,29]. It is also obvious that the proposed controller reduces the chattering and thus yields favorable path following response.

Performance comparison for path following control problem is shown in Tab. 2. As shown, the proposed controller achieves better performance compared with the controllers proposed in [28,29] in the case of path following control.

Table 2: Performance comparison for path following control problem

Approach	IAE	ITAE	ISE
APID-SOSMC	24.0608	128.4390	0.1741
APID-TOSMC	17.7851	93.4210	0.1012
ATOSMC	19.9854	95.3514	0.1416

4 Conclusions

An adaptive PID-based higher order SMC approach for nonlinear systems is presented in this paper. The proposed approach integrates a third order SMC with PID controller with a view of combining their advantages and overcoming their drawbacks. The proposed approach is adaptively tuning the PID parameters in the real time to be used properly for any real time applications. By combining the adaptive control with the SMC, the developed approach allows for the relaxation of the boundness condition of uncertainty level in conventional SMC. The robustness and efficiency of the developed approach is validated mathematically and through simulations. The developed approach achieves lower chattering and error that other conventional SMC approaches. Future work may consider working toward finding a generalized SMC approach to able to vary the order of the SMC to any value as needed.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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