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Event-Triggered Sliding Mode Control Versus Time-Triggered Sliding Mode Control: A Comparative Study

Mohammed K. Hamza[1], Safanah M. Raafat[2], Shibly A. Al- Samarraie[3]
[1,2,3] Control and System Engineering Department, University of Technology, Baghdad, Iraq
[1]60115@uotechnology.edu.iq, [2]safanah.m.raafat@uotechnology.edu.iq,
[3]shibly.a.alsamarraie@uotechnology.edu.iq

Abstract— *unlike continuously triggered techniques, event-triggered strategies update the control actions based on specific conditions. Consequently, the energy consumption will be reduced while maintaining performance and stability. Compared to the traditional (periodic) implementation of SMC, event-triggered sliding mode controller (ET-SMC) requires 101 control action modifications, 33.9 % less than periodic SMC implementation. The proposed triggering rule technique is shown to be feasible and closed-loop stable. A positive lower bound for inter-event execution time prevents Zeno-type behavior. The mathematical model of a linear time invariant system which is chosen to be a Direct Current servo motor (DC servo motor) is simulated to show the advantages of the recommended technique over conventional sliding mode technique. The Direct Current servo motor (DC servo motor) is chosen as the mathematical model of a linear time invariant system which simulated to show the advantages of the recommended technique over conventional sliding mode technique.*

Index Terms— *Event control, Triggered control, Sliding mode, Event triggered control, Aperiodic control, DC servo motor.*

I. INTRODUCTION

Due to their widespread applications in nearly all domains, computer-controlled systems have become an indispensable topic of study in contemporary control theory. Several design methods for investigating the stability of computer-controlled systems have been proposed in the literature [1], [2]. Due to its ease of conception and application, the sample-and-hold method is the most popular and prevalent one of these techniques. Though, this process results in additional workload for the hardware of the systems (namely processors) and wasteful use of energy. Mainly in network-based control systems, where unnecessary frequent assessments are performed with periodic triggered control. Event-Triggered (ET) control, introduced in this article, is an innovative sampling approach in which the control action is updated on request only. In this technique, the trigger policy that ensures the system's stability also determines the intervals between control signal updates. Thus, the system's stability is maintained while unnecessary control action updates is minimized. The concept of event-based control design is originally described in [3], with subsequent in-depth discussions taking place in [4]-[9]. More recent developments and practical uses of event-triggered control are discussed in [10]-[12]. In recent years, (ET) method has been devised in the literature to account for knowledge of the plant's nominal model. This has resulted in the Model-Based ET Control (MB-ETC), which has been implemented alongside the SMC [13]-[15]. This strategy has been successfully combined with SMC, to produce a control strategy that guarantee satisfactory and robust performance for the controlled system against system perturbation [16]-[18]. In SMC structure, there are two stages (phases) of operation: the reaching stage and the sliding stage [19]-[21]. During the reaching stage, the system states' trajectories are driven

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to the sliding surface then the states move toward the origin asymptotically [22]-[24]. The need for adaptation in dealing with modeling perturbation that may influence the system in an unavoidable manner, necessitates the employment of SMC that is associated with ET technique [25]. We present an SMC that is based on event-triggering technique which employs only aperiodic measurements. The method's primary advantage is to eliminates the need for continuous assessment of control action while maintain a positive lower constraint on the inter-event time. In addition, the aperiodic ET-SMC ensures system's reliable operation under any specified steady-state constraint. In this method, the SMC and the trigger rule are constructed concurrently to ensure the stability of an ET system while implementing event trigger limitations. In this paper, we develop traditional SMC first in order to be able to show the superiority of the proposed ET-SMC. The same linear system mathematical model is used for both controllers. The system stability with the application of ET-SMC is investigated extensively. Using the suggested triggering mechanism, we demonstrate the sufficient condition for aperiodic ET-SMC that guarantee closed loop system stability. The following points summarize the principal contributions of this study.

1. Develop a sliding mode controller activated by events, where the sliding manifold's upper and lower bounds can be modified by changing the controller's settings.
2. For a certain type of linear systems, a triggering rule is developed to guarantee that the trajectory of the system state is always contained inside the enclosed region of the sliding surface (manifold).
3. Suitable condition is developed and maintained to avoid the building up of trigger events.

The remaining parts of this paper are organized as follows: In Section II, the problem formulation and a general overview of the SMC layout is presented. The theoretical background of integrating event trigger approach with SMC is covered in Section III. The stability analysis of the closed-loop system and the impact of using an event-triggering mechanism is given in Section IV. The mathematical model of the LTI system is given is in Section V. All the results obtained from applying the theory described in this paper is presented in Section VI this includes both traditional SMC and event-triggered SMC. Finally, the main significant outcomes of this paper is outlined in Section VII.

II. PRELIMINARIES AND PROBLEM FORMULATION

In order to simplify our explanation of the sliding mode system and to offer brief knowledge about event-triggered control, we will consider the following model of the LTI system:

$$\dot{x} = Ax + B(u + d) \tag{1}$$

where, $x \in R^n$ are the states of the system, $u \in R$ is the scalar control input, $A,$ and B are the system dynamics matrices with suitable dimensions, and d is the matched system model uncertainty. The paper operates under the premise of the following perturbation conditions:

Assumption 1. the disturbance $d(t)$ has a finite upper bound, this implies that there exists d_o such that $sup_{t\geq 0}| \, d(t) \leq d_o$

Assumption 2. The original system is in regular form.

First, for the classical SMC design, the sliding variable is given as follows [19]:

$$s(x) = \lambda^T x \tag{2}$$

where, $\lambda \in R^n$ are the sliding variable parameters with $\lambda = 1$. Then the sliding manifold can be described as follows [19]

$$S = \{x \colon s(x) = \lambda^T x = 0 \tag{3}$$

The goal is to guarantee, in finite time, that the system given in Eq. (1) always operates within the sliding mode. The sliding motion will be introduced to the system by designing suitable control policies. This can be obtained by differentiating $s(x)$ with respect to time:

$$\dot{s} = \lambda^T\, Ax + \, \lambda^T\, Bu + \, \lambda^T\, Bd \tag{4}$$

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Sliding mode can be produced using the following control law [19]:

$$u = (\lambda^T B)^{-1}(\lambda^T Ax + K\ sign\ (s)) \tag{5}$$

where K $> sup_{t\geq 0}|\lambda^T Bd|$ and provided that $\lambda^T B \neq 0$

Substituting Eq. (5) in Eq. (4) to obtain the following:

$$\dot{s} = -Ksign\ (s) + \lambda^T \mathrm{Bd} \tag{6}$$

For the system's trajectory to reach the sliding manifold, the following requirements must be valid:

$$s\dot{s} \leq -\eta\ |s|\ , \eta > 0 \tag{7}$$

where, η is the reachability factor which is well-known in the literature of sliding mode control. This criterion guarantees that the surface of sliding system is accessible in a finite time. The control rule is often implemented in practical applications through the use of digital processors. Therefore, the continuous-time control formulation may be converted into a digital control statement by simply substituting discrete states for the continuous ones, where the value of control action is fixed until the subsequent triggering instant, as described in the following:

$$u = (\lambda^T B)^{-1}(\lambda^T Ax + Ksign(s(t_i))) \tag{8}$$

at $t \in [t_i, t_{i+1})$, we look at how the execution of an event-triggered structure influences the stability of a system using discrete control given in Eq. (8). The instants at which the control input is sent to the plant are denoted by the sequence: $(t_i)_{i=0}^{\infty}$.

Inter-event time, or T_{in}, is defined as $T_{in} = (t_{i+1} - t_i)$, the plant error $e(t) = (x(t_i) - x(t_{i+1}))$ is introduced into the system for all times, because of the controller's discrete implementation.

It is generally agreed that due to the discontinuity of the control rule of SMC, it can not be implemented directly on a digital platform. Thus, the application of ET-SMC can serve as one solution for this problem. In this work, both the highest permissible disturbance and the sampling interval are included in the design procedure of the ET-SMC proposed in this paper. They are employed to establish the top bound of the sliding trajectory, i.e., The sampling interval and disturbance restriction used to determine the steady-state bounds of the trajectory of a system. Which enhanced the system's steady-state performance.

III. EVENT-TRIGGERED SLIDING MODE CONTROL

In ET-SMC shown in *Fig. 1 (a),* the bound that surround the system states at steady-state is insensitive to changes in sampling frequencies or other aspects of the plant. The steady-state boundary in sliding mode is completely determined by the event parameter in the presence of disturbances. This property makes event-triggered SMC applicable for achieving any target steady-state boundaries. Such system motion is known as Practical Sliding Mode (PSM), and the frequency area in which they occur is known as the Practical Sliding Mode Band (PSMB). The system's path from the initial state $x(t_o)$ at time t is denoted by the notation $x(t, x(t_o)\ )$ [25, 26].

Definition (Practical Sliding Mode): Take into consideration the system given in Eq. (1) and the sliding surface given in Eq. (2) for every stable sliding function $s(x(t))$. The system is in Practical Sliding Mode if, for any $t > 0$, the sliding trajectories are constrained to the neighborhood of the sliding manifold by the bound for all times. The band of possible sliding trajectories shown in *Fig. 1 (b)* is known as the Practical Sliding Mode Band (PSMB) [25].

Designing a switching gain to force the system states into PSM is the main objective of ET-SMC. We develop sufficient criteria that enable us to first design the ET scheme and then to select the steady-state bound of the sliding trajectory. The primary goal of ET-SMC design is to implement the PSM by designing a switching gain. PSM gain condition is comparable to classical sliding mode gain condition. In order to construct the steady-state band of the sliding trajectory, this study first establishes necessary criteria for that [25, 26].

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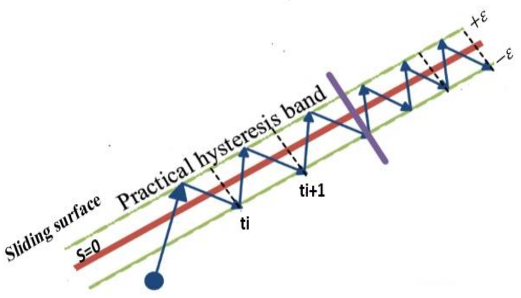
Proposition: considering the system given in Eq. (1) and the control law given in Eq. (8), suppose that the value of α > 0 is chosen such that [25]:

$$\| \lambda \| \; A \; \| \| \; e \; \| < \alpha \qquad (9)$$



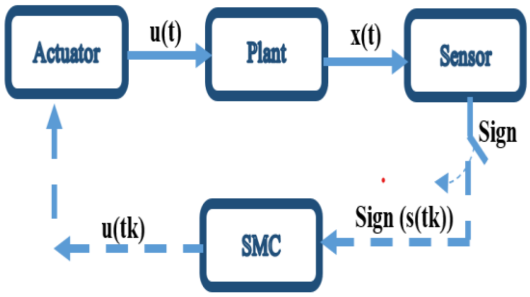


FIG. 1 (A). PRACTICAL SLIDING MODE BAND (PSMB). FIG. 1 (B). BLOCK DIAGRAM REPRESENTATION OF THE PROPOSED SYSTEM.

For all t ≥ 0, the steady- state boundary of the system's trajectories is set by the value of α, hence, it must be chosen according to the design restrictions. The maximum value of α that ensures the system performs effectively can be determined at any time. The maximum steady-state bound occurs with little computing effort only for high values of α. If this condition holds, then the system is controlled according to the PSM law given in Eq. (8). The gain value of the system can be obtained using the following equation [25]:

$$\mathrm{K} > sup_{t\geq 0}|\lambda^T \mathrm{Bd(t)}| + \alpha \qquad (10)$$

The Lyapunov function can be used as proof that a PSM does exist [19].

$$V = \frac{1}{2}s^2 \qquad (11)$$

The following equations demonstrate that the control law of Eq. (8) brings the sliding trajectories of the system states to the neighborhood of s, as described in Eq. (3), for all times $t \in [t_i, t_{i+1})$. By differentiating V with respect to time the following is obtained:

$$V = s(t)\dot{s}(t)$$
$$V = s(t)(\lambda^T Ax(t) + \lambda^T Ax(\mathrm{ti}) - \mathrm{ksign(s(ti))} + \lambda^T \mathrm{Bd(t)}$$
$$= -s(t)(\,\lambda^T Ae + \mathrm{ksign(s(ti))} - \lambda^T \mathrm{Bd(t)}$$
$$= |s(t)||\lambda^T Ae| - s(t)\mathrm{ksign}\big(\mathrm{s(ti)}\big) + |s(t)|\;|\lambda^T \mathrm{B}|d_0 \qquad (12)$$

Substituting Eq. (10) and Eq. (9) in Eq. (12), it yields

$$\dot{V}(s(t)) \leq |s(t)|\|\lambda\|\|A\|\|e\| - s(t)\;K\;sgn\;(s(t_i)) + |s(t)||\lambda^T B|d_o$$
$$\dot{V}(s(t)) = |s(t)|\alpha - s(t)\;K\;sgn\;(s(t_i)) + |s(t)||\lambda^T B|d_o \qquad (13)$$

Take $K = \mu + |\lambda^T B|d_o$, yields,

$$\dot{V}(s(t)) = |s(t)|\alpha - |s(t)|sign\;(s(t)) \times K\;sign\;(s(t_i)) + |s||\lambda^T B|d_o \qquad (14)$$

IV. EVENT-TRIGGERING CONDITION

In most cases, the rule's triggering condition is chosen to ensure the stability of the closed-loop system. Thus, the design ensures that a stable sliding motion dynamic exists, and that a PSM exists as well. In the following a rule for conditional triggering [25]:

$$t_{i+1} = \inf\{t > t_i | c||A||e| \geq \;\alpha\} \qquad (15)$$

When the condition given in Eq. (15) is met the necessary instant to generate control action are produced. Then, if the trigger condition is met, the control signal will have been modified (updated).

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The suggested triggering rule for ET control system is examined, along with its impact on system stability. The sequence of trigger events produced by Eq. (15) is represented by $\{t_i\}_{i=0}^{\infty}$.
Assigning a specific control rule to the processor means that ensuring the time between any two successive triggering instants is always less than some finite positive quantity. This quantity is called as the inter-event time interval.
In the present work, the triggering condition is simplified via the following proposition
Proposition (1) Considering the control law and the system given in Eq. (8), and Eq. (1) respectively. Let the series of triggering events produced by Eq. (9) be $\{t_i\}_{i=0}^{\infty}$, and let $\alpha \in (0, \infty)$ is given. The triggering condition is given by :
$t_{i+1} = \inf\{t > t_i : |s| > \rho\, \epsilon\}$
where $0 < \rho < 1$ and ϵ is the boundary layer thickness as a result, the state will be ultimately bounded by $\|x\| \leq \delta(\epsilon, \lambda)$
where δ can be suffeciently small by proper selection of ϵ, and λ
Before proving the proposition, let us define the sets Ω_ϵ and its complement $\Omega_{\epsilon c}$;
$\Omega_\epsilon = \{x : |s(t)| \leq \epsilon\}$
$\Omega_{\epsilon c} = \{x : |s(t)| > \epsilon\}$
proof.
Let the state $x(t)$ initiated in $\Omega_{\epsilon c}$. In this case the derivative of Lyapunov function (Eq.(14)) becomes,
$\dot{V}(s(t)) \leq |s|\alpha - |s(t)|K + |s||\lambda^T B|d_o$
$\dot{V}(s(t)) = |s|[K - \alpha - |\lambda^T B|d_o]$
$\dot{V}(s(t)) = |s|[K - \alpha - |\lambda^T B|d_o]$
$\dot{V}(s(t)) = |s|[\mu - \alpha]$ (16)
Where, $sign\left(s(t_i)\right) = sign\left(s(t)\right)$. since $|s| > \epsilon$, the event will be triggered through each sampling period T_o, i.e.,
$t_{i+1} = t_i + T_o$
Where it is assumed that $\alpha(t_{i+1})$ will be less than μ, so the region defined by the set Ω_ϵ in finite time and after that the triggering will be take on place when the state leave the region inside Ω_ϵ defined by $\{x : |s| \leq \epsilon\rho\}$. Therefore, one can assume that the state will not leave the following positively invariant set defined by $\overline{\Omega}_\epsilon = \{x : |s| < B\epsilon\}$, where B>0 which is function to T_o and the system dynamics. Eventually, the steady state error can be computed as [21].
Where by proper selection of ϵ and λ, its value can be adusted to the desired one.

V. MATHEMATICAL MODEL (ELECTRICAL DC SERVO MOTOR)

In this paper, electrical DC servo motor is used as the system plant, which is modelled as linear time invariant system. Several technical systems depend on the precise control of the servo motor's position and speed, including Computerized Numerical Control (CNC) machines, industrial robots, winding machines, and others [27]. DC servo motor systems need to have good resilience under the influence of the perturbation term in addition to other desirable qualities, such as no overshoot, fast response, and high tracking behaviour [28]-[29]. The system behaviour is defined by the following equation [30]**:**

$$\ddot{\theta} = -\frac{b}{J}\dot{\theta} + \frac{kt}{J} * u + \frac{1}{J}d \qquad (17)$$

θ: position (angle) of the rotor motor (rad)
$\dot{\theta}$: velocity in (rad/sec)
$\ddot{\theta}$: acceleration (rad/sec^2)
j and b are moment of inertia and damping coefficient, respectively. u is the torque current command in (Amp). kt is the torque constant, and d is the external disturbance in (N. m), the value of d is assumed

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to be constant throughout this paper (*d=1*). The nominal values of the system parameters are denoted by b_n and j_n, while the uncertainty values are denoted by b and J that are shown in Tables I and II. Where $\delta_b = 40\% \times b_n$, and $\delta_J = 40\% \times J$.

The tracking error is the difference between the actual position output and its desired value. The error in tracking is given by $e = \theta - \theta_d$ where θ_d represents the desired output value. Using the error and its derivative, we can define the system's states as follows: $x_1 = e,\ x_2 = \dot{e}$.

TABLE I. THE VALUES OF THE SYSTEM DYNAMIC PARAMETERS

Parameter	Nominal value Units	Units
b	8.8×10^{-3}	Nm^2/rad
J	5.77×10^{-2}	Nms^2
kt	0.66	Nm/A

TABLE II. THE NOMINAL, MAXIMAL AND MINIMAL UNCERTAINTIES VALUES OF THE SYSTEM DYNAMIC PARAMETERS

Parameter	Nominal	Maximal	Minimal
b/J	0.125	0.216	0.092
kt/J	11.55	16.188	6.935

In this work, a value of $\frac{Pi}{4} = 0.078$ is used for θ_d and this number is being used as a step input. Thus, Eq.(17) in state-space format as shown below:

$\dot{x_1} = x_2$

$$\dot{x_2} = -\frac{bn}{jn} + \frac{kt}{jn}\mathrm{u} + \Delta(x,u) \tag{18}$$

Where $\Delta(x,u)$ is the term of perturbation that incorporates both the external disturbance and the parameter's uncertainty.

$$\Delta(x,u) = -\frac{\Delta b}{\Delta jn} + \frac{kt}{\Delta jn}\, u_{dis} \frac{1}{jmin} d \tag{19}$$

The SMC for the servo DC motor system is designed in the manner described below:

$$s = x_1 + x_2 \tag{20}$$

The sliding variable *s* dynamics is expressed as:

$$\dot{s} = \lambda \dot{x}_1 + \dot{x}_2 \tag{21}$$

Substituting Eq. (18) in Eq. (21):

$$\dot{s} = \lambda x_2 - \frac{bn}{jn} x_2 + \frac{kt}{jn} u + \Delta(x,u) \tag{22}$$

$$\text{Let } u = u_1 + u_2 \tag{23}$$

$$u_2 = u_{dis} = -k * sign(s) \tag{24}$$

Substituting Eq. (23) in Eq. (22) above:

$$\dot{s} = \lambda x_2 - \frac{bn}{jn} x_2 + \frac{kt}{jn}(u_1 + u_2) + \Delta(x,u) \tag{25}$$

When the system state is on the sliding surface, the control action u_1 is devoted to cancel the nominal term in Eq.(25) as follow:

$$u_1 = \frac{jn}{kt}\left(x_2\left(\frac{bn}{jn} - \lambda\right)\right) \tag{26}$$

According to the controller *u* is given by:

$$u = \frac{jn}{kt}\left(x_2\left(\frac{bn}{jn} - \lambda\right)\right) - k(x) * sign(s) \tag{27}$$

In Eq. (27), u represents the whole control action.

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VI. SIMULATION RESULTS

In In this section, a set of comprehensive simulation experiments is conducted using Matlab software to demonstrate the theoretical results presented thorough out the previous sections.
The simulations are carried out in two cases; Case one, classical SMC is developed to stabilize the system dynamics in the presence of perturbation. While in Case two, an event-driven strategy is applied in combination with SMC is used to stabilize the same system used in Case one. In both cases, the applied desired input trajectory which is the position angle (θ_d) is chosen to be equal to $Pi/4$. The initial values for the system states are selected as x = [1,0]. It is worth to mention here, that both controllers maintain stability for the system, however, number of controller updates reduced significantly using ET-SMC which is the main objective of this study.

A. Case One Classical SMC Design

Fig. 2 shows the behaviour of the system states $x_1$and x_2, which clearly move toward the origin asymptotically. The sliding surface (s) and the control action (u) are plotted in *Fig. 3* and *Fig. 4* respectively. *Fig. 5* is showing the phase plane plot of the system states with the application of the controller, where the states trajectory travelled from its initial value and settle down on the controller's sliding manifold after finite amount of time then remain on the sliding manifold for rest of the time. The size band of (s) remains constant unless the time interval or boundaries of disturbance change. *Fig. 6*, shows clearly the ability of the SMC to derive the position angle (θ) to its desired value in about (4.8sec). By examining the above conducted simulation results using classical SMC, it is clear that the controller was able to maintain stability and show robust behaviour in the presence of system perturbation.

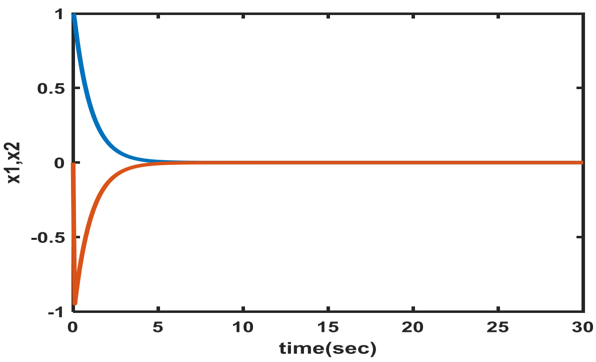

FIG. 2. THE EVOLUTION OF STATES OF THE SYSTEM.

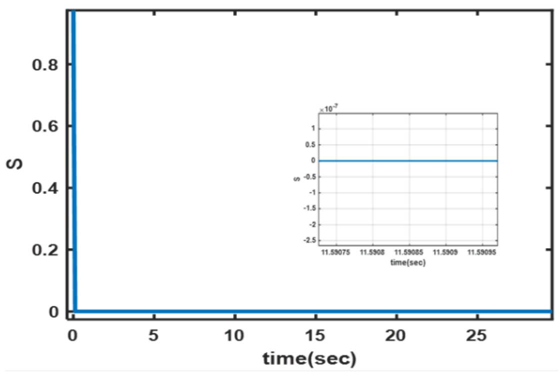

FIG. 3. SLIDING MANIFOLD S.

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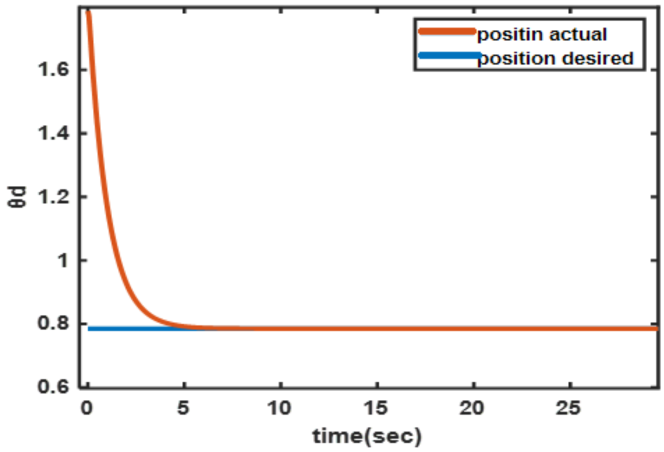

FIG. 4. CONTROL INPUT (U).

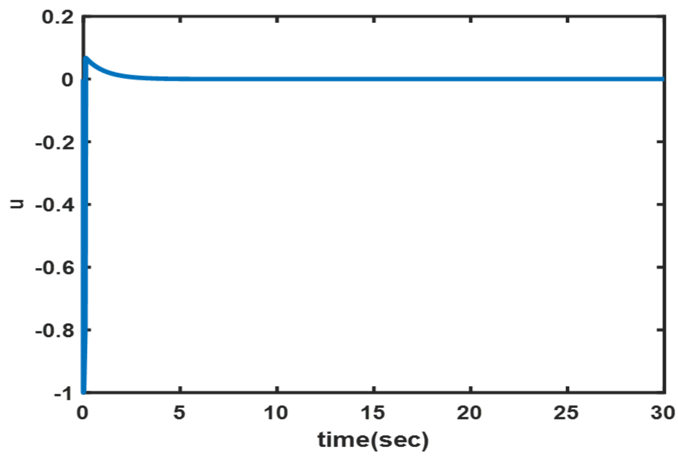

FIG. 5. STATE TRAJECTORY IN PHASE PLANE.

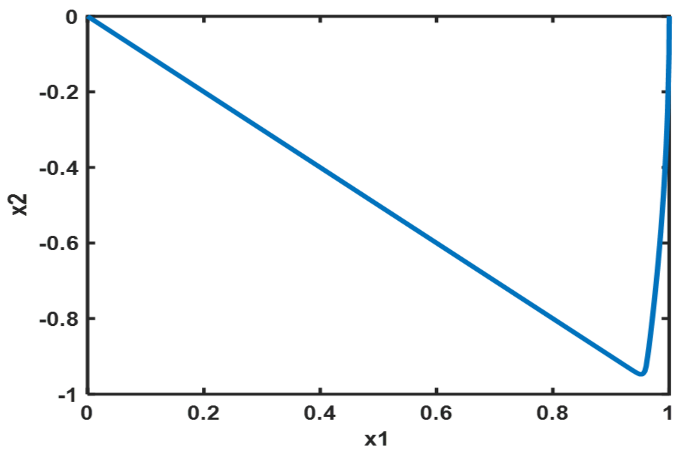

FIG. 6. ACTUAL AND DESIRED POSITION.

It is important to highlight the fact that the control action of the classical SMC applied in this case is updated at a fixed rate of time (continuously) based on constant sampling period. This can lead to

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unnecessary control updates, especially when the system response does not require frequent adjustments to the control action. In this case the number of updates of the control actin equal (6000).

B. Case two ET-SMC Design

In this case, the value of K is designed according to Eq. (10). The parameter (α) is chosen to be equal to 0.1. *Fig. 7* shows the behaviour of the system's states over time. *Fig. 8* shows the phase plan of the system states with the application of the ET-SMC, while the operation of the control action is shown in the *Fig. 9*. It is clear that the ET-SMC controller can easily derive the position angle (θ) to track its reference value as shown in *Fig. 10*.

It is important here to highlight the fact that the sliding surface of the ET-SMC applied in this case is not zero exactly, but it lies within a band given by $\omega_\varepsilon = \frac{\alpha}{\|A\|}$ and the numerical value of the band is found to be equal to 0.01 as shown in *Fig. 11*. This value guarantees the existence of Practical Sliding Mode (PSM). Moreover, it guarantees that the mechanical system behaves in Zeno-free behaviour. Furthermore, the proposed control approach ensures that the lower bound of inter event time T_{in} bounded away from zero by a constant value (0.122), as shown in *Fig. 12*. The quantities of the generated events can be decreased by suitable selection of the event design parameter value (α). A larger value of **α** results in fewer events being generated, hence, requiring less action from the controller.

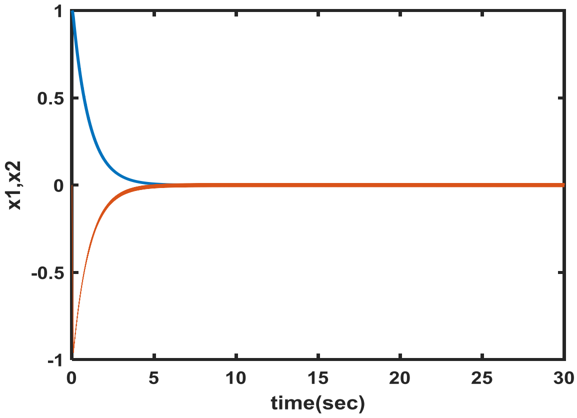

FIG. 7. THE EVOLUTION OF STATES OF THE SYSTEM.

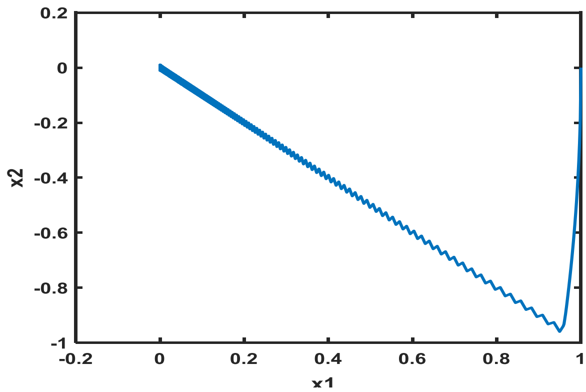

FIG. 8. TRAJECTORY STATE IN PHASE PLANE.

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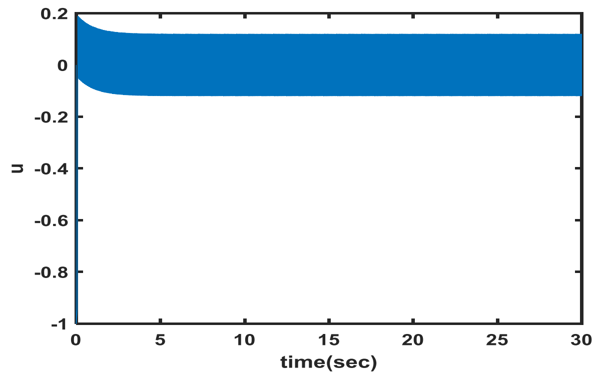

FIG. 9. CONTROL INPUT (U).

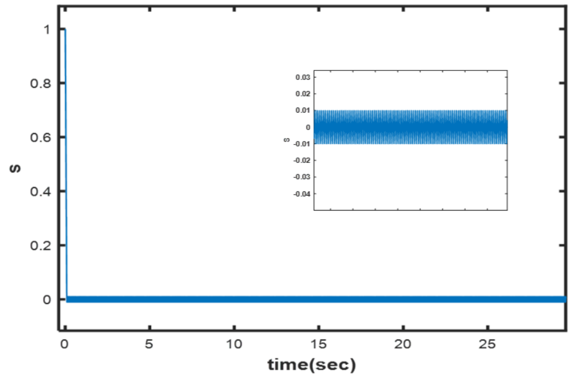

FIG. 10. SLIDING MANIFOLD S.

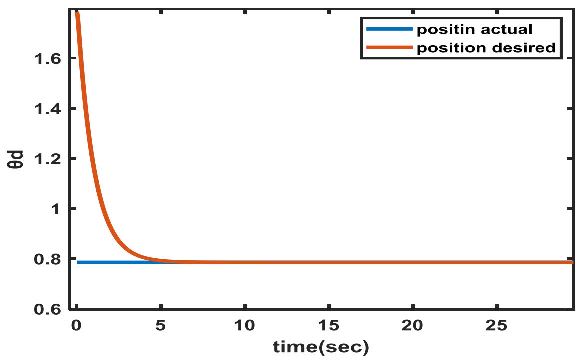

FIG. 11. DESIRED TRACKING.

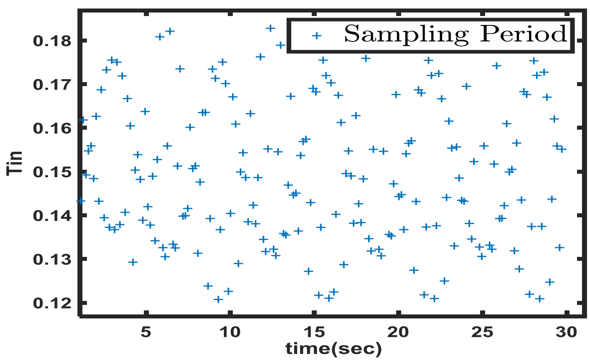

FIG. 12. INTER EVENT TIME (TIN).

Table III shows the effect of using traditional SMC in contrast with ET-SMC. It compares the number of control updates between traditional SMC and ET-SMC scheme. Which lessen the number of updates

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significantly, reduce the amount of control computation, and uses fewer resources without affecting stability or performance which is the main target of this work.

TABLE III. DIFFERENCE BETWEEN CLASSICAL SMC AND ET-SMC

Type of controller	**No. of control updates (u)**
Classical SMC	6000
ET-SMC	2036

VII. CONCLUSIONS

In this paper, a classical SMC and an Event triggered sliding mode control ET-SMC are designed to maintain stability for a class of LTI system. The main outcomes of this paper are outlined in the following points:

1. In order to reduce the consumed energy in the system, a SMC that is based on event-triggering approach is developed. This strategy has significantly reduced the number of control action updates in the system from being (6000) with classical SMC to (2036) with ET-SMC, which means a valuable reduction percentage by 33 %. This is refected mainly on the consumed energy by the two controllers.

2. This feature is highlighted by comparing it to the outcomes of a classical SMC. The simulation experiments are given to demonstrate the efficiency and highlight the difference between the two proposed methods.
3. A new triggering mechanism is developed to ensure stable sliding motion of the system states, hence, maintain closed-loop system stability.
4. The ET-SMC is designed to drive the system states into PSMB by using a switching gain (K), then suitable steady state band (band of possible sliding trajectories) is obtained numerically according to system design specifications that ensures effective performance for the system. The value of (α) affect the band size, larger number of (α) is associated with larger value of the band size.
5. The designed ET-SMC guarantees a Zeno free system by imposing positive lower bound to the inter-execution event time.

As a main outcome of this paper, is that all the above-mentioned findings are demonstrated for the LTI system that under the effect of perturbation (external disturbance and system parameter uncertainty). Finally, applying the suggested ET-SMC technique to be used for nonlinear system is a possible extension for the work proposed in this paper in the future.

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