ARTICLE IN PRESS

ISA Transactions xxx (xxxx) xxx

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Practice article

Improvement of sliding mode controller by using a new adaptive reaching law: Theory and experiment

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HIGHLIGHTS

- The proposed SMC can achieve a high performance with significant reducing of a chattering problem.
- A new adaptive reaching law is proposed to achieve very fast reachability convergence.
- Experiments and comparative results are presented to prove the superior performance of the proposed controller.

ARTICLE INFO

Article history:
Received 29 April 2019
Received in revised form 2 August 2019
Accepted 2 August 2019
Available online xxxx

Keywords:
Sliding mode controller
Exponential reaching law
Chattering
Fast convergence
Robot manipulator
DC motor

ABSTRACT

In this paper, a new sliding mode control (SMC) is applied to a physical nonlinear system. The novelty of this approach is related to the proposed reaching law by overcoming the main limitations of SMC. Unlike existing reaching laws, the suggested one can achieve high performance with significant reducing of a chattering problem and has a very fast convergence time of the system trajectories into the origin. This law benefits from the advantages and overcomes the limitations of both the exponential reaching law (ERL) and the conventional sliding mode control (SMC). Simulation results and comparison study with ERL and SMC are presented and applied on two degrees of freedom robot in order to show the advantage of the proposed adaptive reaching law. Experiments results are performed with electric cylinder (DC Motor) to confirm this proposition in real-time implementation.

1. Introduction

A practical control system should be designed to guarantee the stability of the physical system. As well, its performance should be unaffected by the disturbances generated from the variation of internal parameters of the system, unmodeled dynamics stimulation, and external disturbances. For a nonlinear physical system, the sliding mode control (SMC) is one of the most popular strategies that is widely applied to robotics systems [1–6], and accomplishes the robust performance requirement. In SMC, a switching surface is selected so that the trajectory can start form anywhere and is forced to reach the switching surface in reasonable finite time. Once on the switching surface, the dynamics of the system is reduced to a stable linear time-invariant system which is unrelated to the disturbances regardless of its internal or external sources [7]. Asymptotic convergence of the state trajectories is then easily realized; however, conventional SMC like other nonlinear approaches suffers from several imperfections.

In this context, two major shortcomings can be mentioned. The first one is that SMC ensures an asymptotic convergence to the equilibrium point with convergence time related with the value of selected controls gain. Various control methods have been extended to overcome this problem such as terminal sliding mode control (TSMC) [8] that employs a nonlinear switching surface to ensure the finite time convergence by including a fractional order, which permits to the states trajectories to tend to an equilibrium point faster. Recently, the precision performance of TSMC is increased by enhancing new strategies, for instance, fast TSMC [9] and non-singular TSMC [10].

The second major problem of conventional SMC is coming from the control input that contains the switching function signum (sign(.)). In real time implementation, the switching produced by this function appears in undesirable chattering by the control effort. Therefore, the performance of the system decreases, and the high-frequency unmodeled dynamics may be excited. In some controllers, the switching function is replaced by a continuous approximation, as a saturation function [2]. However, the robustness of the control performance is lost in

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https://doi.org/10.1016/j.isatra.2019.08.010
0019-0578/

Please cite this article as: B. Brahmi, M.H. Laraki, A. Brahmi et al., Improvement of sliding mode controller by using a new adaptive reaching law: Theory and experiment. ISA Transactions (2019), https://doi.org/10.1016/j.isatra.2019.08.010.

the presence of even small disturbances [2]. Many solutions have been developed to eliminate chattering and to reduce the time convergence of the system state trajectories such as second order sliding mode control (SOSMC) [11,12]. The main idea of implementing SOSMC is to permit a switching surface and its consecutive derivative to converge to the equilibrium point and to maintain the switching control under an integral function, which can reduce the undesirable chattering. The performance of SOSMC is improved by introducing some actions such as super twisting control [13,14] and modified super twisting algorithm [15,16]. Nevertheless, the second-time derivative of the switching surface might generate instability of the system, a risk that the unmodeled dynamics and external disturbances amplify.

Numerous conventional reaching laws reported in [17] such as the constant reaching law, constant plus proportional reaching law and power rate reaching law. The constant reaching law (CRL) is commonly used in the control system due to its ability to force the state system to converge to the origin with acceptable convergence time. However, its major problem related to the high control chattering can be obtained, where the attenuation issue of the undesirable chattering becomes an expense of the convergence speed option. This law was extended by the constant plus proportional reaching law in order to overcome the limitation of CRL and it succeeded to a certain degree to reduce the chattering problem [17]. The power rate reaching law (PRRL) is one of the strong propositions that was proposed to deal with the convergence speed. Based on the power rate of the surface, the PRRL ensures a chattering free process along with a fast convergence speed. However, its robustness of the control performance close to the surface may be reduced. Exponential reaching law (ERL) [18] is considered as one of the most important solutions and was proposed to overcome the restriction of CRL. Its importance comes from its ability to reduce the undesirable chattering dilemma for the same CRL convergence speed by using a simple exponential adjustment. It succeeded to achieve a good performance with different robotics systems [19–21]; however, the major problem with this approach is its incapability to increase the convergence speed without affecting or provoking the undesirable chattering problem.

Motivated by the different limitations of the mentioned reaching laws, the idea of this paper is to come up with a response on how to increase the convergence time of the system trajectories without influencing the chattering reduction. Based on that, a new reaching law is introduced to address the mentioned problem by improving the convergence speed of the system trajectories, meanwhile increasing the chattering attenuation process. This law benefits from the properties of ERL and SMC, where it employs a sinusoid term to reduce the chattering and utilizes ERL advantage to provide a fast reaching time to the origin. A simulation and comparison study are proposed and applied on 2-DOF robot to show the robustness of the proposed reaching law and its fast convergence speed compared with SMC and SMC combined with ERL. Experiments are applied on electric cylinder (DC Motor) to prove the feasibility and easiness of this proposition in real time implementation.

This paper is organized as follows. Problem formulation and motivation are described in Section 2. Section 3 presents the proposed reaching law in detail. A simulation and comparison study with SMC and SMCERL are presented in Section 4. An experimental study with electric cylinder (DC Motor) is given in Section 5. Section 6 concludes the research.

2. Problem formulation and motivation

The theory of sliding mode control (SMC) of the non-linear system is well-known in the literature [22]. However, we start with a brief description of this approach to highlight its main advantages and shortcomings. These drawbacks stimulate us to propose a new and effective reaching law approach that will be detailed in the next section. Let us start this section by considering a general non-linear second-order dynamic system as follows:

$$\ddot{x} = f(x, \dot{x}) + g(x, \dot{x})\, u \tag{1}$$

where $f \in \Re^n$ and $g \in \Re^{n\times n}$ are two non-linear functions and g is an invertible matrix. The tracking position error which goes to zero can be defined: $e = x - x^d$ where, $x^d \in \Re^n$ is the desired trajectory. The design of SMC control always starts by the selection of a switching function S in terms of tracking position/velocity errors. Commonly, the sliding surface is chosen as follows:

$$S = \dot{e} + \lambda e \tag{2}$$

where $\lambda \in \Re^{n\times n}$ is a diagonal positive definite matrix. It is important to mention here that the selection of the value of λ plays a dominate role in the convergence rate of the error tracking to zero.

Let us determine the Lyapunov function as: $V(S) = \frac{1}{2}S^T S$, taking its time derivative, we find:

$$\dot{V} = S^T \dot{S} \tag{3}$$

For stability analysis, $\dot{V} < 0$ which leads, $\dot{S} < 0$ if $S > 0$ and $\dot{S} > 0$ if $S < 0$. That leads increase to the switching phenomenon of the control law about $S = 0$. Based on (2) and its derivative, we can propose the following control input:

$$u = g^{-1}\left[\ddot{x}^d - \lambda\dot{e} - f + \dot{S}\right] \tag{4}$$

It is noteworthy from (4) that $\dot{S}$ plays a significant role in the expression of the control input, where it is clear that $\dot{S}$ determines the rate of S and hence if $\dot{S} \ll 0$ for $S > 0$ (and contrary is valid), then the system trajectory forced converges onto $S = 0$. Therefore, the term of $\dot{S}$ is known as the "reaching" law. When the state's system is extremely near to $S = 0$, $\dot{S} < 0$ determines that the state system's closeness to the sliding surface $S = 0$ while $\dot{V} < 0$. Consequently, there is a "switching" phenomenon appearance to maintain the condition: $S\dot{S} < 0$. Various reaching laws have been proposed in literature, taking into consideration the speed of the reaching time. These reaching laws can be summarized as follows [17]:

1. Constant rate reaching law (CRL) [17]:

$$\dot{S}_i = -K_i sign(S_i) \tag{5}$$

where $K_i > 0$ with $i = 1 \ldots n$ is positive constant. The reaching law (5) makes the system trajectory $(e_i, \dot{e}_i)$ converge to the switching surface S_i in reaching time given by: $Tr_i = \frac{|S_i(0)|}{K_i}$ where $S_i(0)$ is the initial value of S_i. So, greater value of K_i is required to ensure a fast convergence; however, it inevitably provokes a grown chattering when the system trajectory moves in the sliding manifold.

2. Constant plus proportional rate reaching law (CPPRL) [17]:

$$\dot{S}_i = -K_{1i} sign(S_i) - K_{2i} S_i \tag{6}$$

where K_{1i}, K_{2i} are positive constants. This law can ensure a convergence rate with reaching law $Tr_{1i} = \frac{1}{K_{1i}}\ln\frac{K_{2i}|S_i(0)| + K_{1i}}{K_{1i}}$. Expression (6) is one of the strongest reaching laws that provides a fast convergence rate without reducing the chattering phenomenon.

3. Power rate reaching law (PRRL) [17]:

$$\dot{S}_i = -K_i |S_i|^{\sigma} sign(S_i) \tag{7}$$

where $0 < \sigma < 1$. The law (7) is able to provide a reaching time given by: $Tr_{2i} = \frac{|S_i(0)|^{(1-\sigma)}}{(1-\sigma)K_i}$. The advantage of this law is its capability to vary the reaching time speed which depends on the position of the state system from the sliding surface. When the system trajectory is far away from the surface, the control law increases the reaching speed and vice-versa is true. The term $|S_i|^{\sigma}$ can guarantee a chattering free process along fast convergence of the desired state which leads to the loss of the robustness which depends on the choice of the power term σ.

It has appeared from the analysis of the three reaching laws that they are very helpful and easily applicable to the design of the SMC. Nevertheless, each of them also has its own minor shortcomings which leads always to the trade-off between the convergence rate speed and chattering reduction or between the chattering reduction and robustness of the control. The common remark between them (the three laws) is that the large value of gain K_i (coefficient of $sign(S_i)$), is required to ensure a fast convergence rate to the desired surface, and in the same time leads to chattering which is damaging as this produces high-frequency dynamics. A kind of adaptive reaching has been proposed in named Exponential Reaching law (ERL) [18] to deal with value of the gains. The ERL is given by:

$$\dot{S}_i = -\frac{K_i}{\mu_i + (1-\mu_i)\,e^{-\alpha_i |S_i|^{p_i}}} sign(S_i) \tag{8}$$

where μ_i, α_i and p_i are strictly positive constants with $0 < \mu_i < 1$. As shown in (8), the ERL approach has overcome the drawback related to the gain in the mentioned reaching law (5) by permitting the controller to dynamically adjust to the variations of the switching function S_i. This operation permits to the gain K_i to vary easily between K_i and K_i/μ_i. So, the ERL method can ensure the convergence rate in reaching time [18]:

$$Tr_{3i} \approx \mu_i \frac{|S_i(0)|}{K_i} \tag{9}$$

if α_i in (8) achieves the following condition [18]:

$$\alpha_i \gg \left(\frac{1-\mu_i}{\mu_i\,|S_i(0)|}\right)^{1/p_i} \tag{10}$$

Clearly that ERL concentrates much more on reducing chattering using the innovative law (8). However, the shortcomings observed in ERL are in its capability to eliminate chattering (when the term $K_i sign(S_i)$ is maintained, the ability of chattering reduction is restricted) and its limitation to increase the convergence speed without influenced chattering attenuation as shown in (9) (when we decrease the reaching time, the term K_i increases which causes the chattering phenomenon. It is remarked that the state of the controller system not overlap perfectly to the reference trajectory due to continuing low degree of chattering. As a promising solution in this paper, we enhanced the reduction of the chattering by the ERL by nearly eliminating the chattering and improving the reaching speed without any effect on the chattering elimination via a sinusoid term adjustment. The proposed adaptive reaching law is chosen in such a way that it will able to associate the advantages of the reaching laws (5) and (8).

3. Proposed adaptive reaching law

This section presents the development mathematics of the proposed adaptive reaching law that can associate the advantages of the mentioned reaching laws, and ensures a convergence time less than the provided by ERL. The proposed adaptive law is designed using damping sinusoid in nature, and is given by:

$$\begin{cases} \dot{S}_i = -\dfrac{K_i}{H(S_i)} sign(S_i) \\ H(S_i) = \zeta_i + (1-\zeta_i)\,e^{-\alpha_i|S_i|}\cos(\beta_i|S_i|) \end{cases} \tag{11}$$

where β_i and α_i are strictly positive constants. the gain $0 < K_i < 1$ and $0 < \zeta_i < 1$. Note here that ζ_i in (11) is the same like μ_i in (8). The both β_i and α_i belong to the following second order polynomial:

$$\begin{cases} S_i^2 + 2\alpha S_i + \omega_n^2 = 0 \\ \omega_n^2 = \alpha_i^2 + \beta_i^2 \end{cases} \tag{12}$$

The proposed reaching law (11) is worked as following:

- Initially $S_i \neq 0$ and is large because of the initial condition of the closed loop system;
- The selection of β_i and α_i is done to fulfill: $e^{-\alpha_i|S_i|}\cos\beta_i|S_i| \approx 0$ which leads to $H(S_i) = \zeta_i \ll 1$;
- Since $H(S_i) \ll 1$ leads to $\frac{K_i}{H(S_i)} \gg 1$, in such case, the trajectory will slowly converged to $S_i = 0$;
- While $|S_i| \approx 0$ and $H(S_i) \to 1$ leads to extremely low chattering of the system's outputs due to: $H(S_i) = K_i < 1$.

The term $e^{-\alpha_i|S_i|}\cos\beta_i|S_i|$ able to cross the zero many times before reaching the origin or equilibrium point. This property may give this term the ability attending to the origin prior to whatever exponential function. It worthy to mention that the exponential function is a constantly asymptotic function with respect to the origin and consequently relatively coincides to the equilibrium point on finite time.

Proposition 3.1. *The reaching law obtained in (11) provide always a faster convergence to equilibrium point than the provided by ERL [18], for the identical K_i,.*

Proof. Let us start by presenting the reaching time provided by the ERL proposition [18]:

$$Tr_{3i} = \frac{1}{K_i}\left(\mu_i\,|S_i(0)| + (1-\mu_i)\int_0^{|S_i(0)|} e^{-\alpha_i|S_i|^{p_i}} dS_i\right) \tag{13}$$

Now, we can find the reaching time (Tr_{4i}) given by the proposed adaptive reaching law. The reaching law (11) can be rewritten as follows:

$$(\zeta_i + (1-\zeta_i)\,e^{-\alpha_i|S_i|}\cos(\beta_i|S_i|))dS_i = -K_i dt \tag{14}$$

Integrating (14) between zero and Tr_{4i} and it should be noted that $S_i(Tr_{4i} = 0)$, one has:

$$\begin{aligned} Tr_{4i} &= \int_{S_i(0)}^{0} \frac{\left(\zeta_i + (1-\zeta_i)\,e^{-\alpha_i|S_i|}\cos(\beta_i|S_i|)\right) dS_i}{-K_i sign(S_i)} \\ &= \int_0^{S_i(0)} \frac{\left(\zeta_i + (1-\zeta_i)\,e^{-\alpha_i|S_i|}\cos(\beta_i|S_i|)\right) dS_i}{K_i sign(S_i)} \end{aligned} \tag{15}$$

If $S_i < 0$ for all $ti < Tr_{4i}$:

$$Tr_{4i} = \int_0^{-S_i(0)} \frac{\left(\zeta_i + (1-\zeta_i)\,e^{-\alpha_i|S_i|}\cos(\beta_i|S_i|)\right) dS_i}{K_i} \tag{16}$$

If $S_i > 0$ for all $ti < Tr_{4i}$:

$$Tr_{4i} = \int_0^{S_i(0)} \frac{\left(\zeta_i + (1-\zeta_i)\,e^{-\alpha_i|S_i|}\cos(\beta_i|S_i|)\right) dS_i}{K_i} \tag{17}$$

According to (16) and (17), we have:

$$Tr_{4i} = \int_0^{|S_i(0)|} \frac{\zeta_i dS_i}{K_i} + \int_0^{|S_i(0)|} \frac{\left((1-\zeta_i)\,e^{-\alpha_i|S_i|}\cos(\beta_i|S_i|)\right) dS_i}{K_i} \tag{18}$$

As result of the integration of (18), the reaching time is given as:

$$Tr_{4i} = \frac{1}{K_i}\left(\zeta_i|S_i(0)| + (1-\zeta_i) \times \left[\frac{\alpha_i}{\alpha_i^2+\beta_i^2}(1-e^{-\alpha_i|S_i(0)|}\cos(\beta_i|S_i(0)|))\right]\right) + \frac{1}{K_i}\left[\frac{\beta_i}{\alpha_i^2+\beta_i^2}e^{-\alpha_i|S_i(0)|}\sin(\beta_i|S_i(0)|)\right] \quad (19)$$

Now let us prove that the proposed reaching law provides a reaching time less than the reaching time provided by ERL [18]. if the value of $|S_i(0)| \gg 1$, the reaching law (19) can be approximated as follows:

$$Tr_{4i} \approx \frac{1}{K_i}\left(\zeta_i|S_i(0)| + (1-\zeta_i)\left[\frac{\alpha_i}{\alpha_i^2+\beta_i^2}\right]\right) \quad (20)$$

As second condition, the gain K_i must satisfy:

$$K_i \approx \frac{1}{Tr_{4i}}\left(\zeta_i|S_i(0)| + (1-\zeta_i)\left[\frac{\alpha_i}{\alpha_i^2+\beta_i^2}\right]\right) \quad (21)$$

Since the comparison of the proposed reaching law will be with the one given by ERL [18]. Now, subtracting (20) from (9) as:

$$Tr_{3i} - Tr_{4i} \approx \mu_i\frac{|S_i(0)|}{K_i} - \frac{1}{K_i}\left(\zeta_i|S_i(0)| + (1-\zeta_i)\left[\frac{\alpha_i}{\alpha_i^2+\beta_i^2}\right]\right) \quad (22)$$

As mentioned in (11) that $\mu_i = \zeta_i$. The eq (22) becomes as:

$$Tr_{3i} - Tr_{4i} \approx \frac{(1-\zeta_i)}{K_i}\left[\frac{\alpha_i}{\alpha_i^2+\beta_i^2}\right] \quad (23)$$

As we remark the term $\frac{(1-\zeta_i)}{K_i}\left[\frac{\alpha_i}{\alpha_i^2+\beta_i^2}\right]$ is always positive, while $0 < \zeta_i < 1$ positive. we can write that:

$$Tr_{3i} - Tr_{4i} > 0, \quad (24)$$

Consequently, the reaching time provided by the proposed adaptive reaching law is always less than the ERL reaching time. The proof is complete.

4. Simulation study

In this section, three numerical simulations are shown for trajectory's tracking of a manipulator with 2-DOFs Pelican prototype robot as shown in Fig. 1. The simulation is done in Matlab(2018a)/Simulink software. The dynamics of the 2-DOFs is written in the form of (1) and the applied control input is given by (4). For each simulation, we substituted the reaching laws (5), (8) and the proposed reaching law (11), respectively. The goal of the simulation study is to compare and to confirm the advantage of the suggested adaptive reaching law.

The dynamic model of the 2-DOFs manipulator is defined as follows:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau \quad (25)$$

where $q \in R^2$ denotes the generalized coordinates vector; $M(q) \in R^{2\times2}$, $C(q,\dot{q})\dot{q} \in R^2$, and $G(q) \in R^2$ are respectively inertia matrix, which is symmetric and bounded, Coriolis and centrifugal torques, and the gravitational torques. $\tau \in R^2$ is the torque input vector. These matrices is defined as follows:

$$M(q) = \begin{pmatrix} M(1,1) & M(1,2) \\ M(2,1) & M(2,2) \end{pmatrix}$$

with, $M(1,1) = l_{c2}^2 m_1 + m_2[l_1^2 + l_{c2}^2 + 2l_1 l_{c2}\cos(q_2)] + I_1 + I_2$; $M(1,2) = M(2,1) = m_2[l_{c2}^2 + l_1 l_{c2}\cos q_2] + I_2$; $M(2,2) = l_{c2}^2 m_2 + I_2$;

$$C(q,\dot{q}) = \begin{pmatrix} -m_2 l_1 l_{c2}\sin(q_2)\dot{q}_2 & -m_2 l_1 l_{c2}\sin(q_2)[\dot{q}_1 + \dot{q}_2] \\ m_2 l_1 l_{c2}\sin(q_2)\dot{q}_1 & 0 \end{pmatrix}$$

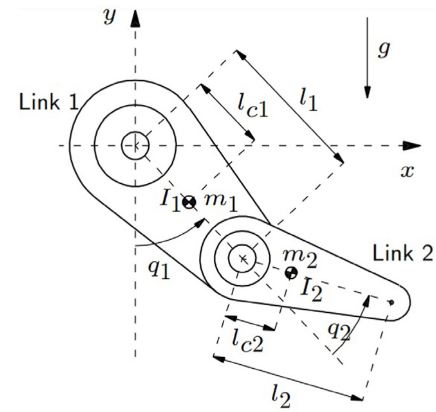

Fig. 1. Two-link of the Pelican prototype robot [23].

Table 1
Parameters of the 2-DOFs robot manipulator [23].

Symbol	Definition	Value	Unit (s)
l_1	Length of the first link	0.26	(m)
l_2	Length of the second link	0.26	(m)
l_{c1}	Distance to the center of mass (Link 1)	0.0983	(m)
l_{c2}	Distance to the center of mass (Link 2)	0.0229	(m)
m_1	Mass of link 1	6.5225	(kg)
m_2	Mass of link 2	2.0458	(kg)
I_2	Inertia rel. to center of mass (Link 1)	0.0229	(kg m^2)
I_2	Inertia rel. to center of mass (Link 2)	0.0229	(kg m^2)
g	Gravitational constant	9.81	(m/s^2)

and

$$G(q) = \begin{pmatrix} (m_1 l_{c1} + m_2 l_{c1})g\sin(q_1) + l_{c2}m_2 g\sin(q_1+q_2) \\ l_{c2}m_2 g\sin(q_1+q_2) \end{pmatrix}$$

The parameters of the 2-DOFs manipulator are given in Table 1.

The robot's dynamics (25) can be rewritten as the general form of the nonlinear system given in (1):

$$\ddot{q} = f(q,\dot{q}) + g(q,\dot{q})\,u \quad (26)$$

where, $g(q) = M^{-1}(q)$, $u = \tau$ and $f(q,\dot{q}) = -M^{-1}(q)(C(q,\dot{q})\dot{q} + G(q))$. Now, we can apply the control input 4 easily. The control objective is to force the real trajectories of the robot to follow the reference trajectories given by:

$$q_{1d} = 1.25 - (\frac{7}{5})e^{-t} + (\frac{7}{20})e^{-4t}$$
$$q_{2d} = 1.25 + e^{-t} - (\frac{1}{4})e^{-4t} \quad (27)$$

All initial joint positions and velocities of the robot are chosen as:

$$q_1 = 0.4\ rad,\ \ q_2 = 1.8\ rad$$

and

$$\dot{q}_1 = \dot{q}_2 = 0\ rad/s.$$

The gains used in the simulation of all controllers are chosen manually based on " trial error" and given in Table 2. It is worthy to mention here that we have used the same value of the parameters common between the proposed approach and SMCERL to evaluate the both approaches under the same conditions.

4.1. Discussion

Classical SMC: The tracking trajectories of q_1 and q_2 is shown in Fig. 2. It is clear from this figure that the SMC controller provides a good convergence to the reference trajectories with small

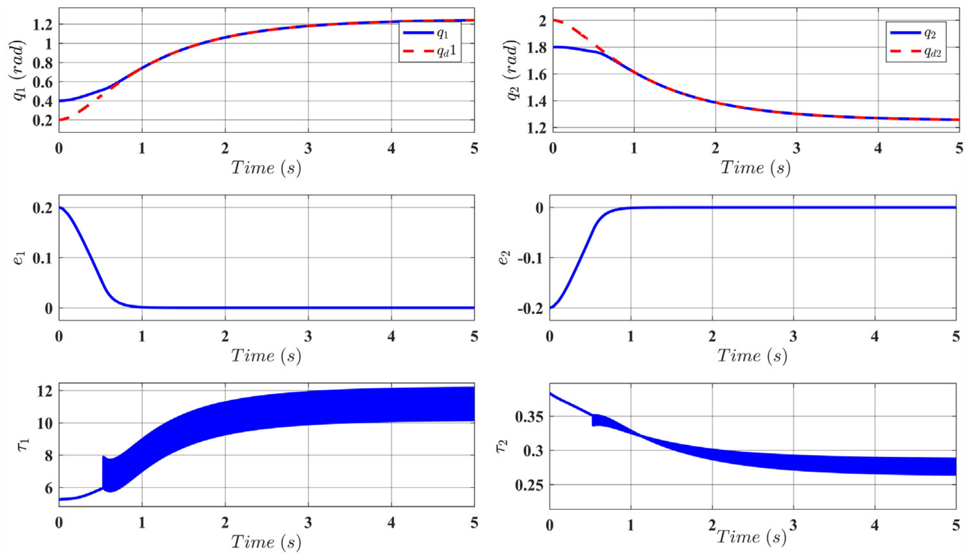

Fig. 2. Evolution tracking of Sliding Mode Controller (SMC).

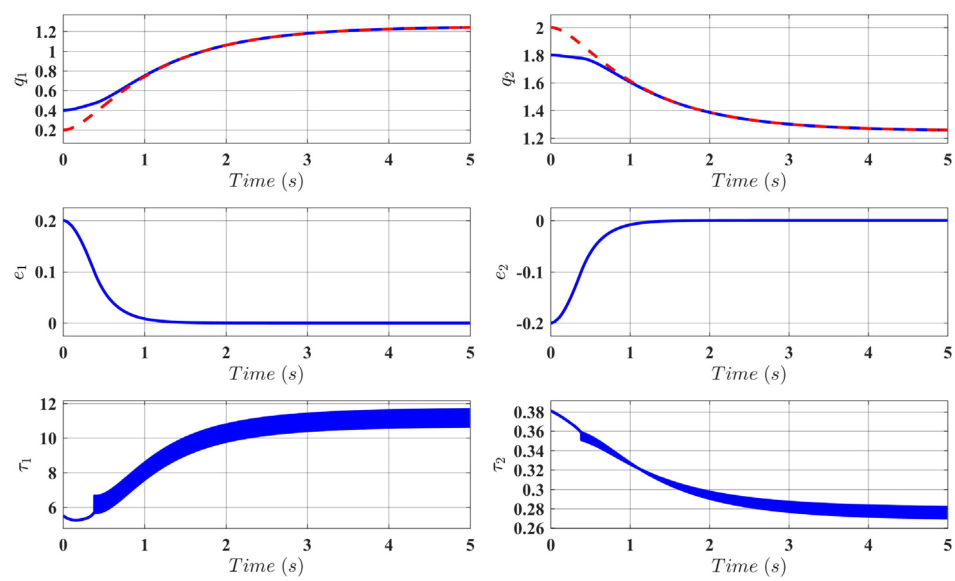

Fig. 3. Evolution tracking of Sliding Mode Controller with Exponential Reaching law (SMCERL).

Table 2
Parameters of the controllers.

Gains	SMC	SMCERL	PRL
K_i	25	2	2
λ_i	2	2	2
α_i	–	20	20
p_i	–	1	1
ζ_i, μ_i	–	0.06	0.06
β_i	–	–	85

errors of tracking. However, the chattering is very important as shown in the last line of Fig. 2 because of the high selection of gains which gives inadmissible torques controls.

Sliding mode control (SMC) with ERL: Fig. 3 presents the tracking trajectory of joints position (q_1 and q_2). It is obvious from this figure that SMCERL provides good results, where the real trajectories are overlapped the reference trajectories. Also, the chattering phenomenon has been reduced compared with the SMC controller that shown in the last line of Fig. 3.

Sliding mode with proposed reaching law (PRL): The performance of the proposed controller is shown in Fig. 4. The important remark is that the proposed controller save the same high performance of SMC and SMCERL, and eliminate totally the chattering phenomenon as shown in the last line of Fig. 4 which proves the feasibility of this proposed approach.

Fig. 5 shows the evolution of the surfaces given by the SMC, SMCERL and proposed PRL. Clearly all controllers drive the surface to meet the origin in finite time, however, the proposed PRL is faster than the two others. Through these results, we conclude that the proposed control proves his superior performance, efficiency, and feasibility compared with conventional approaches.

5. Experiments study

5.1. System characterization

The process that will be controlled in this paper is the electric cylinder shown in Fig. 6. The movement of the moving part of

Please cite this article as: B. Brahmi, M.H. Laraki, A. Brahmi et al., Improvement of sliding mode controller by using a new adaptive reaching law: Theory and experiment. ISA Transactions (2019), https://doi.org/10.1016/j.isatra.2019.08.010.

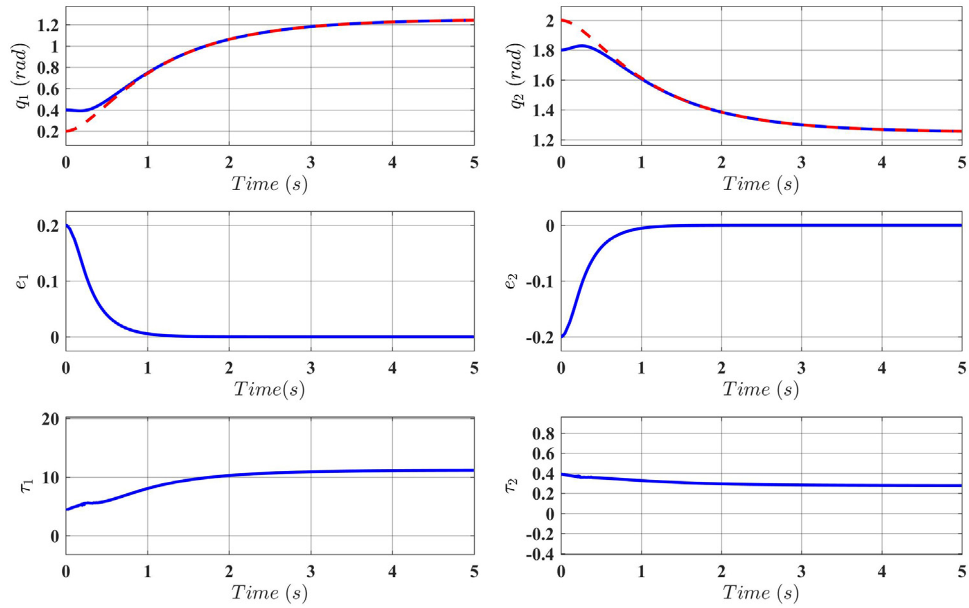

Fig. 4. Evolution tracking of Sliding Mode Controller with proposed reaching law (PRL).

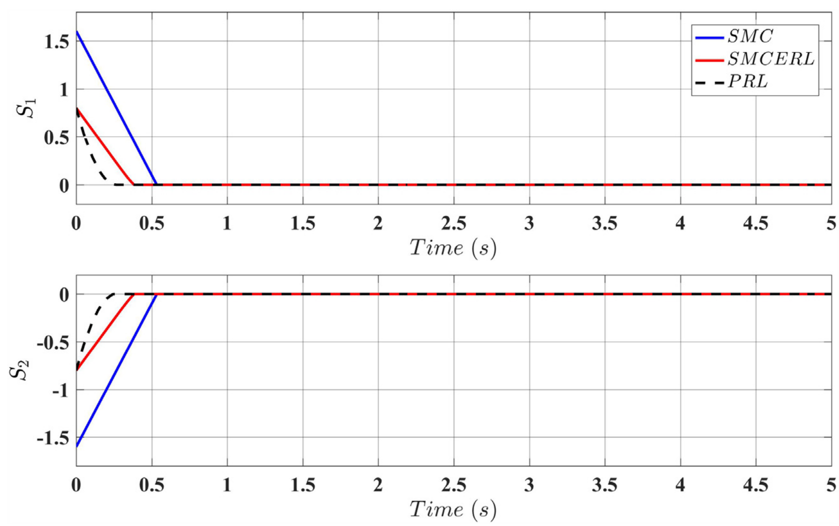

Fig. 5. Evolution tracking of Sliding Mode Controller (SMC).

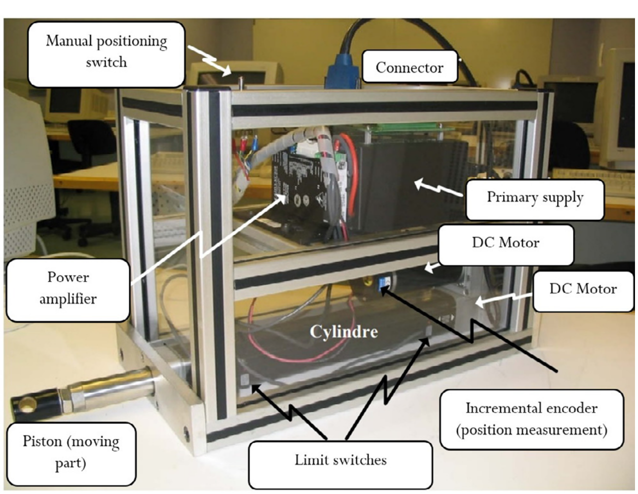

Fig. 6. Electric Cylinder.

this cylinder is actuated by a DC motor which is powered by a power amplifier whose input voltage can vary between −10 and +10 volts. As shown in Fig. 6, the position of the movable part of the cylinder is measured by an incremental encoder.

Fig. 6 shows the working environment of our system. It indicates, among other things, that the inputs/ outputs of the process to be controlled (cylinder) are connected to an acquisition card which is inserted inside a computer running the Windows operating system. Indeed, the input of the power amplifier is connected to the first digital to analog converter (D/A) of the acquisition card while the incremental encoder is connected to the position decoder of this same card. These input–output signals are accessible through the LabVIEW software.

Simplified linear dynamic model of a DC motor is given by:

$$\ddot{x} = f(x, \dot{x}) + g(x)\, u \tag{28}$$

where, $g(x) = J^{-1}$, $u = K\upsilon$ and $f(x, \dot{x}) = -J^{-1}(B\dot{x} + R\tau)$. With: J is rotor's inertia, $B = f_m + (\frac{K_a K_b}{R_a})$ where f_m is rotor's friction coefficient with respect to its hinges. K_a and K_b are motor-torque

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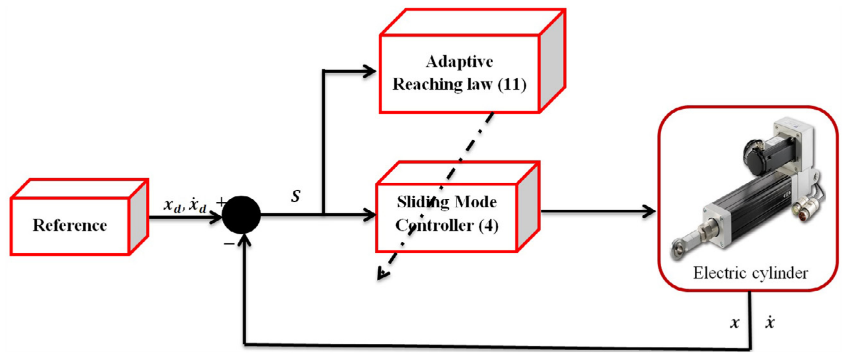

Fig. 7. Diagram scheme of the proposed approach.

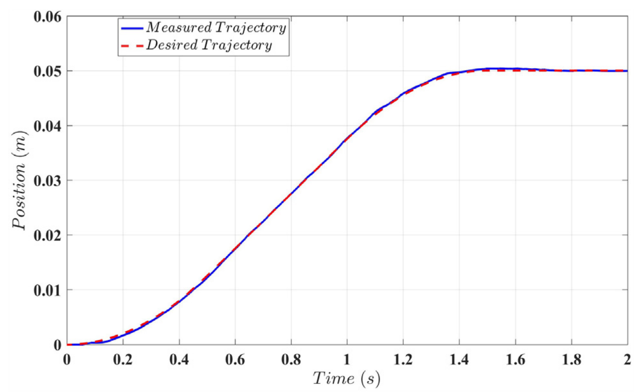

Fig. 8. Tracking trajectory performed by SMCERL.

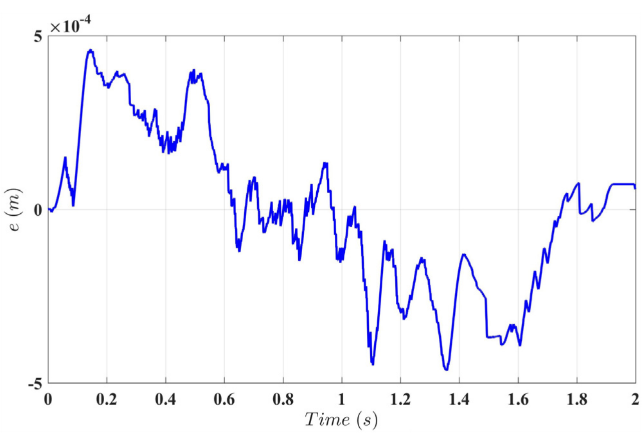

Fig. 9. Tracking error of SMCERL performance (related with Fig. 8).

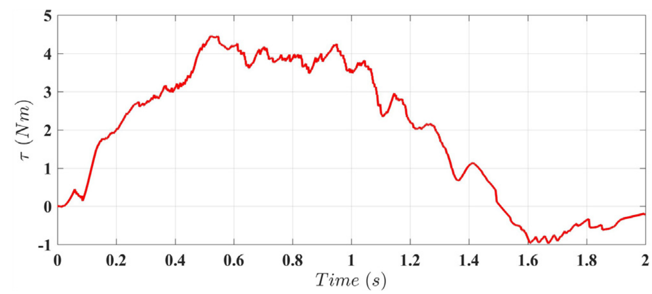

Fig. 10. Control input of SMCERL performance (related with Fig. 8).

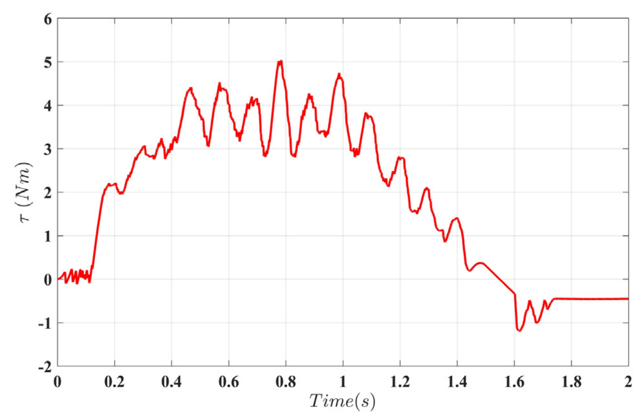

Fig. 11. Tracking trajectory performed by proposed PRL.

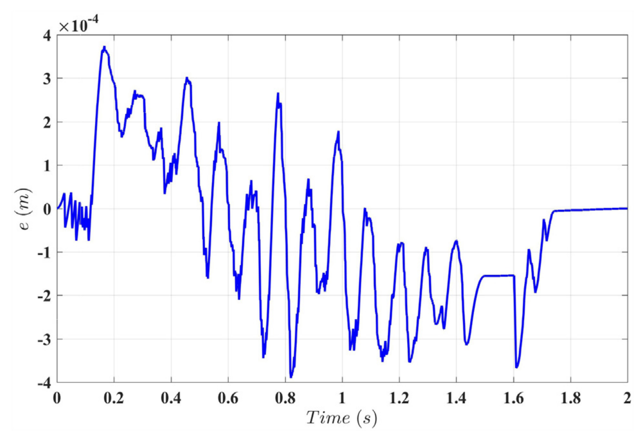

Fig. 12. Tracking error of proposed PRL performance (related with Fig. 11).

constant and back emf, respectively, and R_a armature resistance. $R = \frac{1}{r^2}$, where r is gear reduction ratio and $K = (\frac{K_a}{R_a})\frac{1}{r}$. υ is armature voltage. Now, we can apply the control input 4 easily. the closed loop diagram of the proposed approach is given in Fig. 7. The experiments results are given in next section.

5.2. Experiments results

We applied SMCERL and proposed PRL in the electric cylinder system to validate experimentally the superior performance of the proposed approach compared with conventional approach SMCERL. For both controllers, we use the same value of gains that chosen manually as follows: $K_1 = 5$, $\lambda = 2$, $\mu_i = \zeta_i = 0.05$, $\alpha_i = 0.03$, $p_i = 5$ and $\beta = 8$ (see Fig. 13).

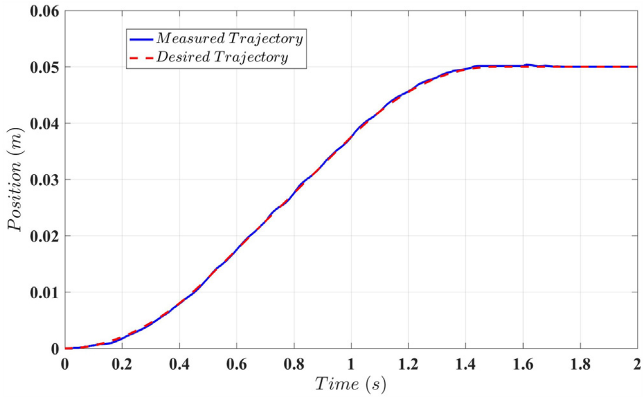

Fig. 13. Control input of proposed PRL performance (related with Fig. 11).

5.2.1. Discussion

Clearly, both controllers SMERL and PRL present a very good tracking trajectory, as shown in Figs. 8 and 10 and Figs. 11 and 13 respectively. However, the proposed control was able to associate between the good tracking of trajectory and the chattering reducing as shown in Fig. 13 compared with SMCERL (Fig. 10). This claim is proved by the convergence the error of the tracking trajectory to zero in Fig. 12. Contrariwise, the evolution of the error of SMCERL converges to a value close to zero as shown in Fig. 9. This phenomenon caused by the chattering effect. These results confirm the efficiency and feasibility of the proposed approach experimentally.

6. Conclusion

In this paper, a sliding mode control (SMC) with a new adaptive reaching law is employed to a nonlinear system. The proposed adaptive reaching law proves its capability to overcome and enhances the performance of SMC. Using the suggested reaching law makes the SMC capable to achieve high performance with significant reducing of a chattering problem. In addition, it has a very fast convergence time of the system trajectories into the origin compared with existing reaching laws. Simulation results and comparison with existing successful approaches are done to show the advantage of the proposed reaching law. Experimental results with electric cylinder system confirm the feasibility and easiness of this approach in real-time implementation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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