An Adaptive Integral Terminal Sliding Mode Control Method for a Chaotic Rod-type Plasma Torch System

Safa Khari, Behrooz Rezaie, Zahra Rahmani

Abstract**—**In this paper, a hybrid adaptive integral terminal sliding mode controller is proposed to stabilize chaotic rod-type plasma torch system. It is assumed that the dynamics of the system are unknown and also the system is exposed to disturbance and unstructured uncertainty. The proposed control scheme is a combination of integral terminal sliding mode and adaptive control methods. Integral terminal sliding mode control provides an appropriate finite-time stability and robustness against uncertainty and external disturbances. In order to approximate unknown dynamics of the system, an online neural network is used. To reduce the approximation error, an adaptive mechanism is also utilized in parallel with the controllers. Simulation results on chaotic plasma torch system indicate the efficiency of the designed hybrid controller and also show the superior performance in presence of disturbance and uncertainty. The response is desirable and without chattering. In addition, unlike previous methods applied to the plasma torch system, there is no need to have information about the unknown part of system and input-output data.

Keywords**—**Integral terminal sliding mode control, adaptive control, neural approximation, plasma torch system.

I. Introduction

Sliding mode (SM) control is a simple robust method for controlling nonlinear systems which can preserve stability in presence of external disturbances and uncertainty in the model of the system. This method provides advantages such as simple design, low cost implementation and robustness against uncertainty [1]. The basic idea of SM control is based on defining a sliding surface on which the states of the system are converged using a discontinuous control law, and thereby, the system stability can be guaranteed.

In recent years, by defining various sliding surfaces, several SM-based control methods such as terminal sliding mode (TSM), integral sliding mode (ISM) and so on have been suggested to provide chattering-free and finite-time stability [2]. Unlike SM control method, TSM control method is based on the exponential nonlinear sliding surface which provides faster convergence of system states [2]. Several types of TSM control such as fast TSM, nonsingular TSM and nonsingular fast TSM control methods have been proposed for different control objectives [2], [3]-[7].

In summary, SM and TSM control methods are powerful methods providing desirable settling time, suitable response to uncertainty and external disturbance and simplicity of design and implementation. Nevertheless, the main problems of these methods is chattering, which is undesirable in control systems, and must be eliminated via the proper method. In addition, these methods need rather exact model of the system, if the studied system has unknown dynamics without any known bound, these methods alone are not applicable.

ISM method is a suitable control that is based on integral sliding surface. In this control method the convergence error and chattering is reduced due to the existence of integral part in sliding surface [8]

In this paper, a combination of an integral terminal sliding mode (ITSM) controller and an adaptive controller is proposed to control a chaotic plasma torch system in order to have a chattering-free and fast response and also to deal with uncertainty and external disturbances. In this control scheme, chattering problem in TSM method is resolved by the idea of combining the terminal sliding surface with an integral function as proposed in [9]. The objective of selecting this structure for sliding surface is to provide chattering elimination and a high response speed.

At the aforementioned research, to solve the problem of unknown system dynamics, the adaptive neuro-fuzzy inference system (ANFIS) is used; however its main disadvantage is requiring a pre-training data of unknown part of the system for initial training. But in the method proposed in this paper, a neural approximation part with radial basis function (RBF), accomplishes online approximation process that it will be used to approximate the possible unknown part in the derivative of Lyapunov function without requiring initial input-output data. The adaptive controller is also designed to compensate the errors caused by neural approximation and external disturbances.

The paper organization is as follows. In section II, the

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system is described. Hybrid control scheme is proposed and explained in section III. In section IV, simulation results are provided, and finally, section V gives conclusion remarks.

II. SYSTEM DESCRIPTION

Plasma torch system is a chaotic system which is widely used in industrial applications. Therefore, improving its efficiency in industrial procedures, such as metal cutting and spraying molten metals on different surfaces is of great importance. One of the major challenges in these industrial operations, particularly in the process of cutting metals and components, is accuracy in manipulating materials. Obviously, occurrence of chaos in such systems will reduce the quality of final product. Therefore, controlling undesired chaos phenomenon is one of the most important objectives for the plasma torch system [6], [7].

In this paper, according to the studies in [6], [7], [10], [11], a class of third-order nonlinear equations are considered for the plasma torch system as below:

$$\dddot{F} + \mu_2\ddot{F} + \mu_1\dot{F} + \mu F = \pm F^3 \tag{1}$$

where $F, \dot{F}, \ddot{F} \in R$ and $\mu, \mu_1, \mu_2 \in R$ are the quantities of plasma field and the system parameters, respectively. The parameters of (1) depend on the characteristics of thermal physics, such as arc current, flow rate of plasma gas and plasma torch machine [7]. In this paper, without loss of generality, we only consider $-F^3$ in the above equations. Moreover, the parameters are assumed to be $\mu_1 = 50$ and $\mu_2 = 1$ based on the researches accomplished in [6, 7]. In addition, μ that is named as gap parameter, is chosen so that the plasma torch system have chaotic behavior.

If it is considered that $F = x_1$, $\dot{F} = x_2$ and $\ddot{F} = x_3$, then the system (1) can be rewritten in the following form:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 \\ \dot{x}_3 &= -\mu x_1 - 50x_2 - x_3 - x_1^3. \end{aligned} \tag{2}$$

where the vector of system states $\underline{x} = [x_1 \quad x_2 \quad x_3]^T$ are the quantities of the plasma filed.

For $\mu < 0$, $[0 \quad 0 \quad 0]^T$ and $\underline{x} = [\pm\sqrt{-\mu} \quad 0 \quad 0]^T$ are the equilibrium points of the system, which are stable for $0 < \mu < 50$ and $-25 < \mu < 0$, respectively. By reducing the value of system parameter μ, the plasma torch system performs chaotic behavior [7]. Besides, on the basis of bifurcation and maximum Lyapunov exponent analyses, by considering the system parameter as $\mu = -130$, the system states will have chaotic behavior, and the zero equilibrium point of the system will become unstable [8]. The phase portrait of the system is demonstrated in Fig. 1.

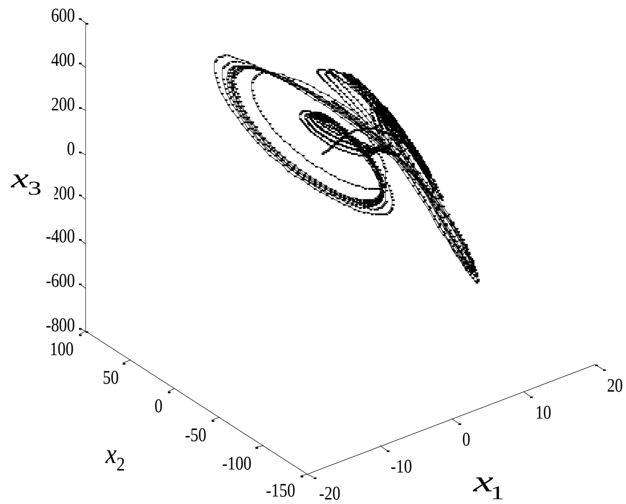


Fig. 1. Phase portrait of chaotic rod-type plasma torch system [13]

Plasma torch system is expressed as (3) with $\mu = -130$, by adding disturbance $d(t)$, and unstructured uncertainty Δf, and by applying control signal $u(t)$, in order to control chaos and stabilize unstable equilibrium point:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 \\ \dot{x}_3 &= 130x_1 - 50x_2 - x_3 - x_1^3 + \Delta f + u(t) + d(t) \\ &= f(x) + u(t) + \Delta f + d(t) \end{aligned} \tag{3}$$

Where $f(x)$ is an unknown function without any initial data.

Disturbance and uncertainty reduce the quality of the processes, such as cutting and covering metal surfaces, in plasma torch system. From practical point of view, initial process leads to extremely small disturbance in the system [6]. Also, there exists a grey probe in plasma torch to bring out gas sample, whose direction can cause disturbance in the system [12].

The inequalities $|d(t)| < \gamma$ and $|\Delta f| < \delta$ are assumed for disturbance and uncertainty, respectively.

III. PROPOSED CONTROL SCHEME

The block diagram of the proposed control system, as demonstrated in Fig. 2, consists of a neural approximation part, an ITSM controller and an adaptive controller.

In the hybrid controller proposed in this paper for plasma torch system, if the system has unknown dynamics, a neural approximator with RBF neural networks is used for online approximating the unknown part without requiring initial input-output data.

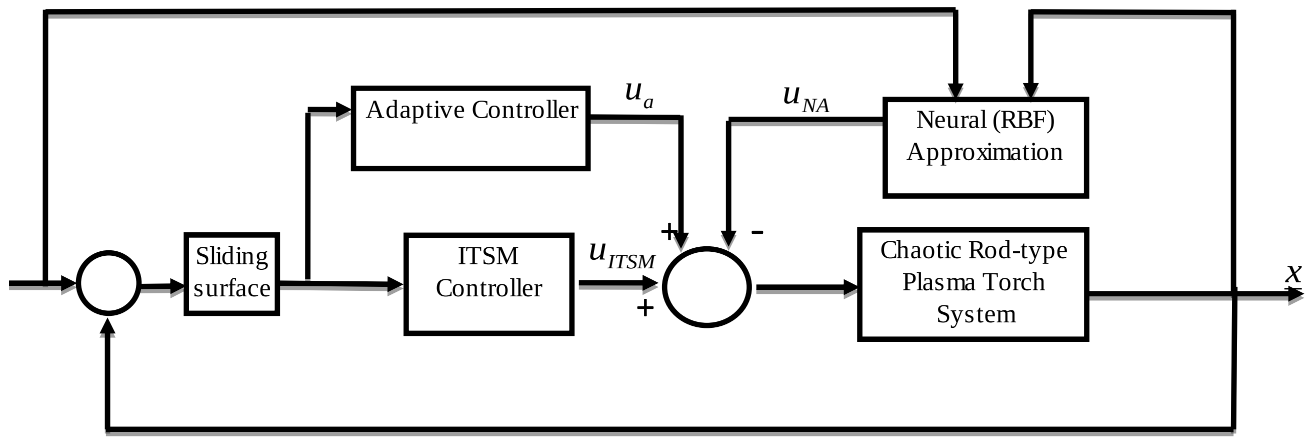


Fig. 2. Block diagram of the hybrid adaptive control scheme

Additionally, this approximation leads to the elimination of unknown terms of the system in Lyapunov function, and the remained dynamics can be stabilized by ITSM. In addition, to reduce the approximation error, an additional adaptive mechanism is also used in parallel with the other components.

A.Integral Terminal Sliding Surface

To design the ITSM controller based on [9], desired sliding surface is defined as:

$$S(x) = x_3 + a x_1^{\frac{p_1}{q_1}} + b x_2^{\frac{p_2}{q_2}} + \int (c_1 x_1 + c_2 x_1^{\beta}) dt. \quad (4)$$

where the coefficients p_i and q_i ($i = 1, 2$) are positive odd constants satisfying $p_i < q_i$. In addition, a, b, c_1, c_2 and $1 < \beta < 2$ are design constant parameters. The range of β is because of increasing the convergence speed.

By considering appropriate control inputs, the system stability is proven via Lyapunov stability theory which can be described as follows.

By differentiating the sliding surface, we have:

$$\begin{aligned} \dot{S} &= \dot{x}_3 + a\frac{p_1}{q_1} x_1^{\frac{p_1}{q_1}-1} \dot{x}_1 + b\frac{p_2}{q_2} x_2^{\frac{p_2}{q_2}-1} \dot{x}_2 + c_1 X_1 + c_2 X_1^{\beta} \\ &= f(x) + a\frac{p_1}{q_1} x_1^{\frac{p_1}{q_1}-1} x_2 + b\frac{p_2}{q_2} x_2^{\frac{p_2}{q_2}-1} x_3 \\ &\quad + c_1 X_1 + c_2 X_1^{\beta} + d(t) + \Delta f + u(t). \end{aligned} \quad (5)$$

By considering $f_T(x)$ as below:

$$\begin{aligned} f_T(x) &= f(x) + a\frac{p_1}{q_1} x_1^{\frac{p_1}{q_1}-1} x_2 + b\frac{p_2}{q_2} x_2^{\frac{p_2}{q_2}-1} x_3 \\ &\quad + c_1 X_1 + c_2 X_1^{\beta}. \end{aligned} \quad (6)$$

$$\dot{S} = f_T(\underline{x}) + \Delta f + d(t) + u(t). \quad (7)$$

where $f_T(x)$ is an unknown function that it can be approximated via a RBF-type neural approximation part in online mode and without pre-training input-output data.

B.Neural Approximation

The approximation of $f_T(x)$ denoted by $\hat{f}_T(x)$ can be calculated as:

$$\hat{f}_T(x) = \hat{w}^T \varphi(x) \quad (8)$$

$$\hat{w} = [\hat{w}_1, \hat{w}_2 ..., \hat{w}_n]^T \quad (9)$$

$$\varphi(x) = [\varphi_1(x), \varphi_2(x) ..., \varphi_n(x)]^T \quad (10)$$

$$\varphi_i(x) = \exp\left(\frac{-\left\| x - c_i \right\|^2}{2b_i^2}\right); i = 1, 2, ..., n. \quad (11)$$

where the weights of NN are $\hat{w}_i$, and φ_i are radial basis functions. Also c_i and b_i are constant parameters.

According to the universal approximation property of NN [14], a continuous function can be approximated by an ideal neural network so that the approximation error remains bounded. Hence, the unknown function $f_T(x)$ can be indicated as below:

$$f_T(x) = w^{*T}\varphi(x) + \varepsilon^*(x) = \hat{w}^T\varphi(x) + \tilde{w}^T\varphi(x) + \varepsilon^*(x) \tag{12}$$
$$\left\|\varepsilon^*(x)\right\| \le \varepsilon$$

where $\tilde{w} = w^* - \hat{w}$. In (12) w^* and $\hat{w}$ are respectively ideal weights and NN weights in approximation, ε^* is the approximation error for the special case $w = w^*$, and ε is an upper bound of the approximation error ε^*.

According to (12), the derivative of the sliding surface can be rewritten as follows:

$$\dot{S} = f_T(\underline{x}) + \Delta f + d(t) + u(t) = \hat{w}^T\varphi(x) + \tilde{w}^T\varphi(x) + \varepsilon^*(x) + d(t) + u(t) \tag{13}$$

where $\tilde{w} = w^* - \hat{w}$, and according to (8), $\hat{w}^T\varphi(\underline{x})$ is the approximation of $f_T(\underline{x})$ which is shown by $\hat{f}_T(\underline{x})$.

C. Neural Approximation

Consider the plasma torch system of (3). The control signal $u(t)$ is suggested as below:

$$u(t) = u_{ITSM} + u_{NE} + u_a \tag{14}$$

where u_{ITSM}, u_{NE} and u_a are the control signals obtained from ITSM controller, neural approximation and adaptive controller blocks respectively.

Thus, the above control signals have been considered as below:

$$u_{ITSM} = -\eta_1 S - \eta_2\,\mathrm{sgn}(S) \tag{15}$$
$$u_a = \frac{-\alpha.S}{|S| + \lambda} \tag{16}$$
$$u_{NE} = -\hat{f}_T = -\hat{w}^T\varphi(\underline{x}) \tag{17}$$

In (15), η_1, η_2 are constant coefficients of u_{ITSM}. In (16), u_a is the control law of the adaptive controller to compensate the errors caused by neural approximation, which approximates $f_T(\underline{x})$, and the external disturbances of the system. The adaptation law for updating α is also extracted from the derivative of Lyapunov function, and λ is chosen such that $\int_0^T \lambda dt < \infty$ is satisfied. In (17), φ are the radial basis functions in u_{NE}. In addition, $\hat{w}$ denotes the weights of RBF neural approximation part and updating laws of these weights are extracted from the derivative of Lyapunov function. The updating laws of weights and adaptive control are as follows:

$$\dot{\alpha} = \frac{S^2}{|S| + \lambda} \tag{18}$$
$$\dot{\hat{w}} = -\dot{\tilde{w}} = S.\varphi(\underline{x}) \tag{19}$$

D. Convergence Analysis

The following theorem proves that the states of the system (3) with control input of the form of (14) will converge to the sliding surface $S(t) = 0$ and will remain on it thereafter.

Theorem 1

Considering the plasma torch system described by (3), the control laws in (14), the sliding surface in (4), the unknown function in (8) and the approximation error in (13), the states of chaotic plasma torch system will converge to $S(t) = 0$ and will remain on it thereafter.

Proof

The Lyapunov function is considered as below

$$V = \frac{1}{2}[S^2 + \tilde{w}^T\tilde{w} + (\alpha - \alpha_0)^2] \tag{20}$$

which is a positive definite function, and α_0 is the upper bound of $\left|\varepsilon^* + \Delta f + d(t)\right|$. By differentiating from the Lyapunov function, we have:

$$\dot{V} = S\dot{S} + \tilde{w}^T\dot{\tilde{w}} + \dot{\alpha}(\alpha - \alpha_0) \tag{21}$$

By replacing (13) into (21), it is obtained that:

$$\begin{aligned}\dot{V} &= S[f_T(\underline{x}) + u(t) + d(t)] + \tilde{w}^T\dot{\tilde{w}} + \dot{\alpha}(\alpha - \alpha_0)\\ &= S[\hat{w}^T\varphi^1(x) + \tilde{w}^T\varphi^1(x) + \varepsilon^*(x) + u(t)\\ &\quad + d(t)] + \tilde{w}^T\dot{\tilde{w}} + \dot{\alpha}(\alpha - \alpha_0)\end{aligned} \tag{22}$$

By substituting (14) to (17) into (22), the following equations are obtained:

$$\dot{V} = S[\hat{w}^T\varphi(x) + \tilde{w}^T\varphi(x) + \varepsilon^*(x) + u_{TSM} + u_{NE} + u_a + \Delta f + d(t)] + \tilde{w}^T\dot{\tilde{w}} + \dot{\alpha}(\alpha - \alpha_0) \tag{23}$$

$$\begin{aligned}\dot{V} &= S\hat{w}^T\varphi(x) + S\tilde{w}^T\varphi(x) + Su_{TSM} - S\hat{w}^T\varphi(\underline{x})\\ &\quad - \frac{\alpha S^2}{|S| + \lambda} + \tilde{w}^T\dot{\tilde{w}} + \dot{\alpha}(\alpha - \alpha_0)\\ &\quad + S[\varepsilon^*(x) + \Delta f + d(t)]\end{aligned} \tag{24}$$

Equation (24) is rewritten as below:

$$
\begin{aligned}
\dot{V} = & -\frac{S^2}{|S|+\lambda}(\alpha-\alpha_0+\alpha_0)+\dot{\alpha}(\alpha-\alpha_0) \\
& +S\hat{w}^T\varphi(x)-S\hat{w}^T\varphi(\underline{x})-S^2\eta_1 \\
& -S\eta_2\,\mathrm{sgn}(S)+\tilde{w}^T\dot{\tilde{w}}+S\tilde{w}^T\varphi(x) \\
& +S[\varepsilon^*(x)+\Delta f+d(t)]
\end{aligned} \quad (25)
$$

Since α_0 is the upper bound of $\left|\varepsilon^*+\Delta f+d(t)\right|$, it is acquired that:

$$
\begin{aligned}
S[\varepsilon^*(x)+\Delta f+d(t)] & \le |S|\left|\varepsilon^*(x)+\Delta f+d(t)\right| \\
& \le \alpha_0|S|
\end{aligned} \quad (26)
$$

and (25) is stated as follows:

$$
\begin{aligned}
\dot{V} \le & (\alpha-\alpha_0)[\dot{\alpha}-\frac{S^2}{|S|+\lambda}]-\alpha_0\frac{S^2}{|S|+\lambda}-\eta_2|S| \\
& -S^2\eta_1+\tilde{w}^T\dot{\tilde{w}}+S\tilde{w}^T\varphi(x)+\alpha_0|S|
\end{aligned} \quad (27)
$$

Therefore, the adaption laws in (18) and (19) are selected such that the derivative of Lyapunov function satisfies the stability condition. By replacing them into (27), we have:

$$
\begin{aligned}
\dot{V} \le & -\alpha_0\frac{S^2}{|S|+\lambda}+\alpha_0|S|-S^2\eta_1-\eta_2|S|=\frac{\alpha_0\lambda|S|}{|S|+\lambda} \\
& -\eta_2|S|-S^2\eta_1 \le \alpha_0\lambda-S^2\eta_1
\end{aligned} \quad (28)
$$

By integrating from the two sides of (28) from 0 to T, we have:

$$
V(T)\text{-}V(0) \le (\text{-}\eta_1)\int_0^T|S|^2dt+\alpha_0\int_0^T\lambda.dt \quad (29)
$$

Since $V(T)>0$ and $\int_0^T\lambda dt<\infty$, the subsequent equations are achieved:

$$
\int_0^T|S|^2dt \le \frac{1}{(\eta_1)}[\alpha_0\int_0^T\lambda.dt+V(0)] \quad (30)
$$

$$
\begin{aligned}
\lim_{T\to\infty}\sup\frac{1}{T}\int_0^T|S|^2dt \le & \{\frac{1}{(\eta_1)}[\alpha_0\int_0^T\lambda.dt \\
& +V(0)]\}\lim_{T\to\infty}\frac{1}{T}=0
\end{aligned} \quad (31)
$$

Consequently, it is directly proved that when $t\to\infty$, then $S\to 0$, i.e. it is concluded from (4) that when $t\to\infty$, then states of the system will be converged to the equilibrium point.

□

IV. Simulation Results

In this section, in order to demonstrate the efficiency of the method proposed in this paper, it is applied to the chaotic rod-type plasma torch system, simulation results are shown.

The initial values of the system states are considered as $[5 \quad -2 \quad 3]$. External disturbance is considered as a pulse signal with amplitude of 5 which is applied to the system from 5 sec to 5.7 sec. Besides, compatible additive unstructured uncertainty Δf in closed-loop system with proposed controller is considered as a sine signal.

$$
\Delta f = 0.2\sin(\pi x_1)\sin(\pi x_2)\sin(\pi x_3) \quad (32)
$$

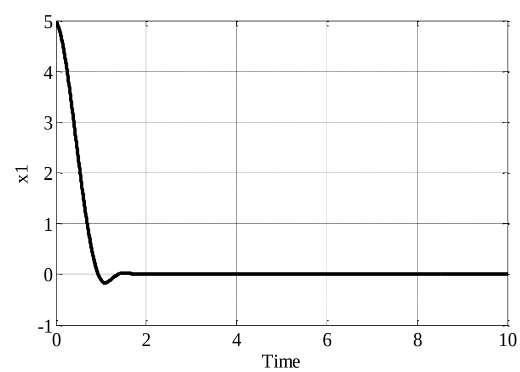
The parameters of proposed ITSM controller and sliding surface in this paper are considered as below:

$$
\begin{aligned}
& a=9.62; b=6.70; p_1=3; q_1=7; \\
& p_2=3; q_2=5; \eta_1=20; \eta_2=10.25
\end{aligned} \quad (33)
$$

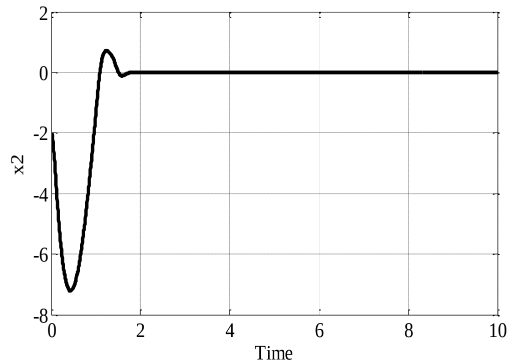
Furthermore, the parameters of adaptive controller and approximation block are assumed to be as following:

$$
\lambda=10^4; c_i=0.01, b_i=\frac{\sqrt{2}}{2} \quad (34)
$$

According to simulation results in Fig. 3, it is observed that there is no chattering at the response, and disturbance has been rejected properly. In addition, pre-training input-output data is not required to approximate the unknown part of the system.



a)



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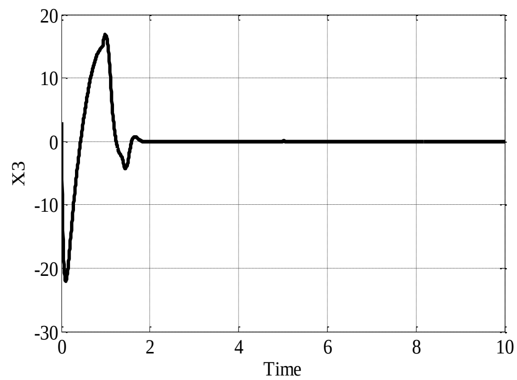
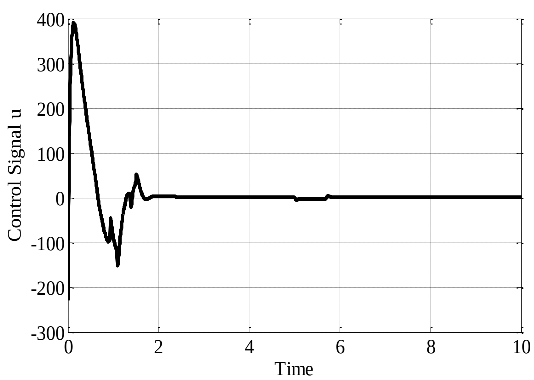


c)



d)

Fig. 3. Adaptive ITSM control for plasma torch system with unknown part in presence of disturbance and uncertainty a) state of system x_1 b) state of system x_2 c) state of system x_3 d) control signal u

V. CONCLUSION

In this paper, a hybrid controller, which is a combination of ITSM controller, RBF-type neural approximator and also adaptive controller, has been designed to control a plasma torch system. In this control method, first, a RBF-type neural approximation block has been designed in order to approximate the unknown part of the system and the uncertainty. Unlike previous methods implemented on plasma torch system, pre-training input-output data are not required for approximation, and approximation has been accomplished in online mode. Besides, ITSM and adaptive controllers have been designed to control the system and to compensate the errors due to neural approximation and external disturbances, respectively. Simulation results of the proposed method implemented on the rod-type plasma torch system have shown the effectiveness of the control scheme, as chattering has been rejected, the response to external disturbances has been improved, and the convergence time of the system states has been enhanced. The proposed control scheme is applicable to any other nonlinear system which is in the class of the system studied in this paper.

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