以模糊正規化強健性平滑控制器實現倒單擺系統之雙調節控制
Dual Regulation Controls of an Inverted Pendulum System Based on a Fuzzy Robust Smoothing Control Scheme

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摘要

一個模糊正規化強健性平滑控制器，用來實現倒單擺系統偏角及位移之雙調節控制在此論文中被提出來。欲操控一個對於偏角敏感且與位移相互耦合之倒單擺系統使其具有強健且平滑的響應，或是對於大角度的偏角控制也能達到最少的平衡點擺動次數及最終位移量達零穩態誤差是極具挑戰性的。滑動模式控制方法是一種強健性控制的機制，可以迫使受控體在具有外來或系統干擾情況下仍能有符合規格要求的性能表現。然而，其既有的抖振問題，若將其實際應用在桿狀的控制系統，如機械臂等，這缺點將被加以放大且控制結果將難以接受。模糊正規化強健性平滑控制方法乃透過正規化轉換及模糊模式化程序將專家認知之滑動控制行為加以建構出來。此具有非線性且連續的近似函數將可以消除抖振現象且不會失去滑動模式控制方法原有之強健性特性。本論文將以倒單擺系統偏角及位移雙調節控制的平滑強健模擬結果來進一步的說明此方法的優異性能。
關鍵詞：模糊，正規化，強健性，平滑控制，倒單擺系統

Abstract

The dual regulation controls, angle and position, of an inverted pendulum balancing system based on a fuzzy normalized robust smoothing control scheme is applied in this paper. It is a challenge to control an angle error sensitive and position-coupled system, an inverted pendulum system, having robust smoothing responses with the fewest hitting times across balance point due to large angle offset, and keeping zero position steady state error. Sliding mode control schemes have robust control mechanisms often used to force the plant to perform under desired specifications, even with external or system disturbance. However, the effect of its inherent chattering problem will be amplified and hard to be accepted for practical applications, especially for the kind of bar-type systems, such as robot arms. A fuzzy normalized robust smoothing control scheme, constructed by the description of intuitive sliding mode control behavior through the procedure of normalized transformation and expert's knowledge construction, can achieve nonlinear continuous approximation and alleviate chatter without sacrificing the robustness of the sliding mode scheme. For further validation, the simulations to control an inverted pendulum balancing system to follow preset specifications smoothly are performed.
Keywords: fuzzy, normalized, robust, smoothing control, inverted pendulum system

I. INTRODUCTION

Inverted pendulum balancing systems are a kind of unstable and nonlinear systems with inherent angle sensitive and position-coupled characteristics, often controlled to explore the robustness or intelligence of control schemes. Such as sliding mode control schemes, fuzzy control schemes, neural networks, and genetic algorithms, etc [1-7].

Sliding mode control schemes, based on Lyapunov's convergent concept to force the system dynamics toward a desired hyperplane, are powerful methods and suitable to deal with nonlinear systems [8-10]. They can offer good

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robustness and transient performance, even in large-signal operations. Therefore, they are often applied to control inverted pendulum systems to express their excellent control characteristics. However, since such control schemes are characterized by a discontinuous function with highly switching action, which will excite un-modeled dynamics, chatter will take place and the steady state performance must be degraded.

Fuzzy control schemes are a kind of rule-based algorithm for the assumption of having expert's experiences, with many parameters and scaling factors, which need to be designed in advance [3]. Margaliot [2] proposed an approach to determining the structure of fuzzy controller for inverted pendulum by fuzzy Lyapunov synthesis. Saez [3] utilized the generalized predictive controller to determine the parameters of the Takagi-Sugeno fuzzy model. Yubazaki [4] considered SIRMs (Single Input Rule Modules) to dynamically connect fuzzy inference model for the stabilization control of inverted pendulum systems. Although these rules can be constructed by quality acknowledgement without plant models, however, how to transfer the knowledge into quantity values and control efforts is still much troublesome.

For parameters updating and searching, intelligent control schemes are introduced in inverted pendulum control systems. Lin [11] proposed a method for adjusting the membership functions of a fuzzy rule base by adaptive sliding mode. Berenji [12] made the action evaluation neural network and the action selection fuzzy network by reinforcement learning to control an inverted pendulum to a neighborhood of the upright position. Lu [13] used the genetic algorithm to generate fuzzy rules and scaling factors for inverted pendulum control automatically.

Every control schemes are necessary solutions and always focused on the stability of inverted pendulum systems only and need large amount calculation and complex procedures to determine their control parameters respectively. Therefore, there are no further discussions about the inverted pendulum control smoothly without swinging and vibrating phenomena, especially for various loadings and large angle offsets. In addition, it is undoubted that the problems of regulation control of angle and position for inverted pendulum balancing systems are worthy of more investigation.

A controller design based on a combination of the sliding mode and fuzzy logic control schemes, which can be applied to highly nonlinear systems to yield superior overall performance, has been reported previously [14-15]. Furthermore, to ensure robust and smooth performance without the gain searching problem for various disturbances, a fuzzy normalized robust smoothing control scheme is proposed by Liu and has been applied in robotic trajectory controls successfully [1]. The controller design is based on the description of intuitive sliding mode control behavior through the procedure of normalized transformation and expert's knowledge construction. This normalized sliding mode function is realized by fuzzy modeling and is able to achieve nonlinear continuous approximation and alleviate chatter without sacrificing the robustness of the sliding mode scheme.

As to the dual regulation controls of the angle and position for an inverted pendulum balancing system, the proposed scheme can provide excellent performance and will be further verified to perform robust and smooth responses, and to have few hitting times of passing stable point without swinging repeatedly.

II. SYSTEM DYNAMICS AND PROBLEM DESCRIPTION

The inverted pendulum system, which consists of a straight-line rail, a cart, a pendulum, and a driving unit, is shown in Figure 1. The cart can move left or right on the rail freely. The pendulum is equipped on the center of the top surface of the cart and can rotate around the pivot in the same vertical plane.

By analyzing the free body diagram of the system, its motion equations can be written as follows [5]:

$$(M+m)\ddot{x} + b_f\dot{x} + ml\ddot{\theta}\cos\theta - ml\dot{\theta}^2\sin\theta = F \qquad (1)$$

$$ml\cos\theta\ddot{x} + (l+ml^2)\theta + mgl\sin\theta = 0 \qquad (2)$$

where the parameters M and m are, respectively, the mass of the cart and the mass of the pendulum in the unit kg, and g=9.8 m/s^2 is the gravity acceleration. The parameter b_f is friction of the cart in the unit N/(m/sec). The parameter l is the length of the pendulum in the unit m. The variable F means the driving force in the unit N applied horizontally to the cart. The variable θ is the angle of the pendulum from up-left position in the unit rad. The variable x is the right direction displacement of the cart in the unit m.

Let $y_1=\theta$, $y_2=\dot{\theta}$, $y_3=x$ and $y_4=\dot{x}$, they can be rewritten as below:

$$(M+m)\dot{y}_4 + b_f y_4 + ml\dot{y}_2\cos y_1 - mly_2^2\sin y_1 = F \qquad (3)$$

$$ml\cos y_1\dot{y}_4 + (l+ml^2)\dot{y}_2 + mgl\sin(y_1) = 0 \qquad (4)$$

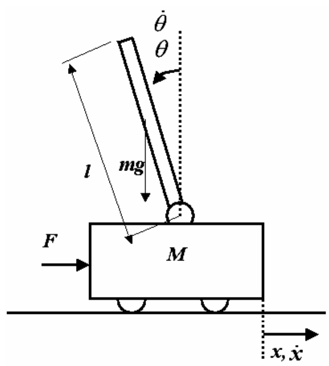

Fig. 1 An inverted pendulum balancing system

Through the substitution of variables, we can get the following equations:

$$\dot{y}_2 = \frac{q}{p} + \frac{r}{p} + F\frac{ml\cos y_1}{p} \tag{5}$$

$$\dot{y}_4 = -\frac{1}{ml\cos y_1}[(l+ml^2)(\frac{q+r+Fml\cos y_1}{p}) + mgl\sin y_1] \tag{6}$$

where $p = m^2l^2\cos y_1 - (M+m)(l+ml^2)$, $q = -b_f ml\cos y_1$ and $r = [m^2l^2y_2^2\cos y_1 + (M+m)mgl]\sin y_1$.

It is obvious that these dynamic equations above are nonlinear. For simplification, we can linear them for small variation ϕ to get the equations as below:

$$(l + ml^2)\ddot{\phi} - mgl\,\phi = ml\,\ddot{x} \tag{7}$$

$$(M+m)\ddot{x} + b_f\dot{x} - ml\ddot{\phi} = F \tag{8}$$

Similarly, let $z_1 = \phi$, $z_2 = \dot{\phi}$, $z_3 = x$ and $z_4 = \dot{x}$, then

$$(l+ml^2)\dot{z}_2 - mglz_1 = ml\dot{z}_4 \tag{9}$$

$$(M+m)\dot{z}_4 + b_f z_4 - ml\dot{z}_2 = F \tag{10}$$

After substituting and calculation, we can get:

$$\dot{z}_2 = -\frac{b_f ml}{p_z}z_4 + \frac{(M+m)mgl}{p_z}z_1 + \frac{ml}{p_z}F \tag{11}$$

$$\dot{z}_4 = -\frac{b_f(l+ml^2)}{p_z} + \frac{m^2l^2g}{p_z}z_1 + \frac{(l+ml^2)}{p_z}F \tag{12}$$

where $p_z = Ml + Mml^2 + ml$.

From equation (11) and equation (12), we can look them as linear dynamic equations with disturbances $-\frac{b_f ml}{p_z}z_4$ and $-\frac{m^2l^2g}{p_z}z_1$, respectively. Surely, they affect their responses for certain control targets each other.

III. THE PROPOSED SCHEME

We consider a second-order nonlinear dynamic system as follows:

$$\dot{x}_1(t) = \dot{x}_2(t)$$
$$\dot{x}_2(t) = f(x_1,x_2) + b\cdot u(t) + g(x_1,x_2,t) \tag{13}$$

where $f(x_1,x_2)$ is the nominal system dynamics, $g(x_1,x_2,t)$ is the system uncertainties and external disturbances, b is the control gain and $u(t)$ is the control effort.

To design a sliding mode controller for equation (13), firstly, we set the sliding hyperplane as follows:

$$\sigma = x_2 + c_1\cdot x_1 \tag{14}$$

Therefore, we can obtain the derivative of the hyperplane as follows:

$$\dot{\sigma} = \dot{x}_2 + c_1\cdot x_2 \tag{15}$$

Secondly, the sliding mode control scheme is formulated as follows:

$$u(t) = u_{eq}(t) + u_s(t) \tag{16}$$

where $u_{eq}(t)$ is the equivalent control effort, and $u_s(t)$ is the switching control effort.

To obtain the nominal control effort or the equivalent control effort, we consider when state is on the switching hyperplane, and $\dot{\sigma} = 0$; then, we have

$$u_{eq} = -\frac{[c_1\cdot x_2 + f(x_1,x_2)]}{b} \tag{17}$$

To assure that sliding behavior occurs, the reaching condition can be obtained by taking the time derivative of a set of Lyapunov functions, $\frac{1}{2}\sigma^2$, to be

$$\sigma\cdot\dot{\sigma} < 0 \tag{18}$$

Then, the switching control effort can be obtained:

$$u_s = (k_1\cdot|x_1| + k_2\cdot|x_2|)\mathbf{sgn}(\sigma) \tag{19}$$

where k_1 and k_2 are positive and obtained based on the bounds of plant perturbations, $\mathbf{sgn}(\sigma)$ is the sign of σ.

1. Normalized switching hyperplane

Consider a normalization process through a transformation by letting

$$x_1^n = n\cdot x_1 \tag{20}$$

$$x_2^n = \frac{n}{c_1}\cdot x_2 \tag{21}$$

where n>0, and is used to ensure that all states x_1^n and x_2^n fall into a normalized phase plane.

Substitute equation (20) and equation (21) into equation (14) to yield

$$\sigma = \frac{c_1}{n}(x_2^n + x_1^n) \tag{22}$$

Therefore, a normalized switching hyperplane is defined as:

$$\sigma_n = x_2^n + x_1^n \tag{23}$$

and the control effort is rewritten as:

$$u = u_{eq} + \frac{c_1}{n}(k_2\cdot x_2^n + \frac{k_1}{c_1}\cdot x_1^n)\cdot\mathbf{sgn}(\frac{c_1}{n}\cdot\sigma_n) \tag{24}$$

This can be further simplified to be

$$u = u_{eq} + \frac{c_1}{n}(h_2\cdot x_2^n + h_1\cdot x_1^n)\cdot\mathbf{sgn}(\sigma_n) \tag{25}$$

where $h_1 = \frac{k_1}{c_1}$, $h_2 = k_2$, and they need to be chosen so as to satisfy the reaching condition, equation (18), and to assure that sliding will occur.

2. Reference rules for normalized smoothing control scheme

To describe the behavior of the sliding mode scheme on a normalized phase plane, we rewrite the switching term of equation (25), $(h_2 \cdot x_2^n + h_1 \cdot x_1^n) \cdot \mathbf{sgn}(\sigma_n)$, with an inferred output, u_f, and form a normalized smoothing controller expressed below:

$$u = u_{eq} + k_\alpha \cdot \frac{c_1}{n} \cdot u_f \qquad (26)$$

where k_α is a positive constant that are used to adjust the envelop of nonlinear continuous approximation near the switching hyperplane.

Intuitively, the ideal sliding mode behavior can be expressed as follows: (1) while the states are far from the normalized hyperplane, a maximum control effort forces the phase trajectory to move toward the hyperplane; (2) while the states are close to the hyperplane, the control effort is diminished accordingly so as to alleviate chatter; (3) the control efforts on the opposite side of the hyperplane have the opposite sign to assure a quasi-sliding behavior; (4) to ensure the property of robustness, the features of sliding behavior are set as conoid. Therefore, the control system can overcome the perturbation automatically for the spreading structure of the control efforts without the problem of over-design.

To realize these intuitive reference rules, we construct several sub-switching surfaces with varied control efforts (i.e. 0.75 $\boldsymbol{u}_{sat}$, 0.5 $\boldsymbol{u}_{sat}$, 0.25 $\boldsymbol{u}_{sat}$, etc.) to partition the normalized phase plane into several regions, shown in Figure 2, and $\boldsymbol{u}_{sat}$ is the maximum control effort. Such a pre-assigned dynamic behavior described above is highly nonlinear and complicated; therefore, we will simplify it and construct an approximate fuzzy model for the controller by fuzzy modeling.

3. Fuzzy normalized robust smoothing control scheme

A fuzzy modeling scheme has been applied to describe complicated systems [16]. The fuzzy model proposed here is constructed by a cell-state space method adopted from the concept of an artificial neural network [17].

We return to the normalized partitioned phase plane shown in Figure 2; let $x_1^n, x_2^n \in [-5, 5]$, and the membership functions be assigned as shown in Figure 3. We use the updating method to obtain the parameters of the rules, and the resultant fuzzy rule description is listed as follows:

If x_1^n is Negative and x_2^n is Negative,
then u_f^1 =0.0290+0.0801 x_1^n +0.0951 x_2^n .
If x_1^n is Negative and x_2^n is Zero,
then u_f^2 =-0.0694+0.1519 x_1^n -0.0656 x_2^n .
If x_1^n is Negative and x_2^n is Positive,
then u_f^3 =0.0084+0.0849 x_1^n +0.0813 x_2^n .
If x_1^n is Zero and x_2^n is Negative,
then u_f^4 =-0.0677-0.0838 x_1^n +0.1529 x_2^n .
If x_1^n is Zero and x_2^n is Zero,
then u_f^5 =0+1.0613 x_1^n +1.0387 x_2^n .
If x_1^n is Zero and x_2^n is Positive,
then u_f^6 =0.0677-0.0838 x_1^n +0.1529 x_2^n .
If x_1^n is Positive and x_2^n is Negative,
then u_f^7 =-0.0084+0.0849 x_1^n +0.0813 x_2^n .
If x_1^n is Positive and x_2^n is Zero,
then u_f^8 =0.0694+0.1519 x_1^n -0.0656 x_2^n .
If x_1^n is Positive and x_2^n is Positive,
then u_f^9 =-0.0290+0.0801 x_1^n +0.0951 x_2^n ,

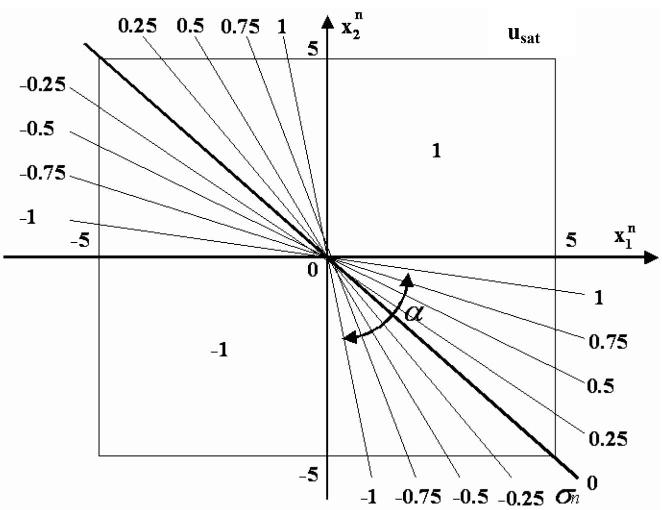

Fig. 2 Partitioned phase plane on a normalized phase plane

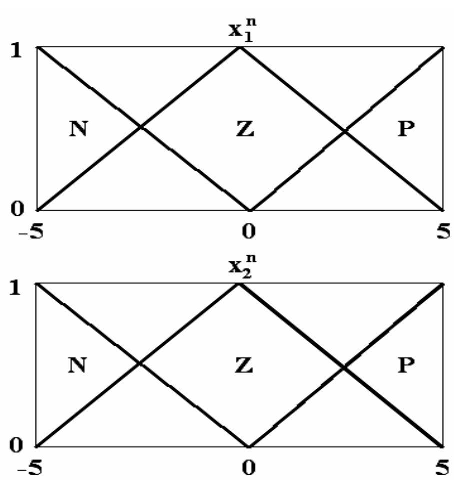

Fig. 3 The membership functions

with $u_f = \dfrac{\sum_{h=1}^{9} A^h \cdot u_f^h}{\sum_{h=1}^{9} A^h}$ (27)

where A^h is the minimum membership of x_1^n and x_2^n, h = 1, 2, ..., 9, and u_f is the defuzzified output. Finally, the sliding mode behavior of this fuzzy model is shown in Figure 4.

IV. THE PROPOSED SCHEME VALIDATION

1. The proposed scheme design

The control system block diagram of the inverted pendulum balancing system is shown in Figure 5, and from the system dynamic equations, the proposed scheme and the directions of system states z_1, z_2, z_3 and z_4, we can design the controller for the inverted pendulum system as follows:

$$u = u_{eq} - k_\alpha \cdot \frac{c_1}{n} \cdot u_f + k_p \cdot z_3 + k_d \cdot z_4,$$

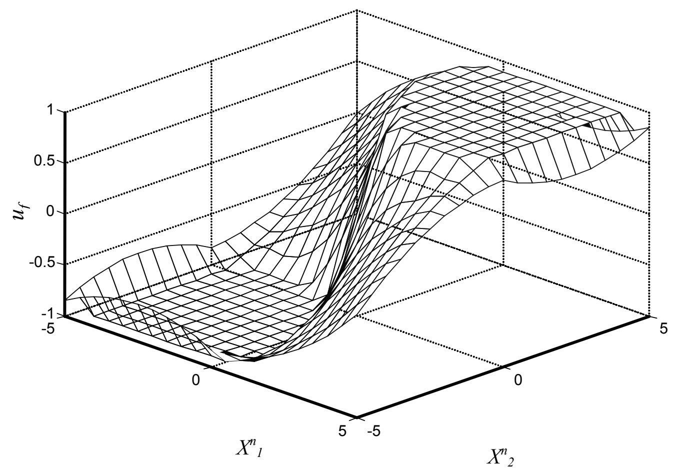

Fig. 4 Dynamic behavior of the fuzzy model in a three-dimension plot

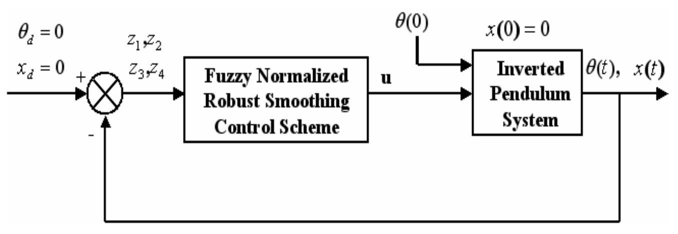

Fig. 5 The control system block diagram

where $u_{eq} = -(M+m) \cdot g \cdot z_1 - \dfrac{c_1 \cdot z_2 \cdot p_z}{m \cdot l}$, c_1 is the slope of the sliding hyperplane, and n, k_α, k_p and k_d are positive.

2. Simulations for different control schemes

In the primary simulation, the parameters of an inverted pendulum system are set as follows: M=0.5 kg, m=0.5 kg, b_f=0.1 NT/(m/sec), l=0.3 m, g=9.8 NT/kg and the saturation value of control effort is 20 NT.

2-1. A sliding mode controller for different initial conditions:

From equation (17) and equation (19), we can design a sliding mode controller and the parameters are set as follows: time constant is 0.5 sec (that is, c_1 =2), k_1=100, k_2=50, k_p=2, k_d=12, and sampling interval is 0.01 sec. For different initial conditions $\theta(0) = 0.2$ rad and $\theta(0) = 0.5$ rad, the results are shown in Figure 6 and Figure 7, respectively. We can find that the system has chattering and swinging responses.

2-2. The proposed scheme for different initial conditions:

We set the specification, time constant, as 0.5 sec (that is, c_1 =2), n=2, k_p=2, k_d=12 and sampling interval is 0.01 sec. For different initial conditions $\theta(0) = 0.2$ rad and $\theta(0) = 0.5$ rad, the results are shown in Figure 8 and Figure 9, respectively. Observing the results, maximum control effort is used to force the controlled system moving toward the desired hyperplane as quickly as possible in the beginning. Then it can overcome the effects of uncertain perturbations by converging along the pre-set sliding regimes. In addition, the overall control process is very smooth.

2-3. The proposed scheme for large offset:

To further verify the robust characteristics of the proposed controller, we also set the same specification, time constant, as 0.5 sec (that is, c_1=2), n=2, k_p=2, k_d=12 and sampling interval is 0.01 sec for a large offset, $\theta(0) = 0.785$ rad and the results are shown in Figure 10. Observing the results, the inverted pendulum balancing system also performs excellent responses and the overall dynamics are still very smooth.

V. CONCLUSIONS

We have presented a fuzzy normalized robust smoothing control scheme for the dual regulation controls of the angle and position of an inverted pendulum system. Observing the simulation results, some attractive features of the proposed controller are listed as follows:

1. We can control an inverted pendulum to have smooth response with the few hitting numbers to pass balance point.

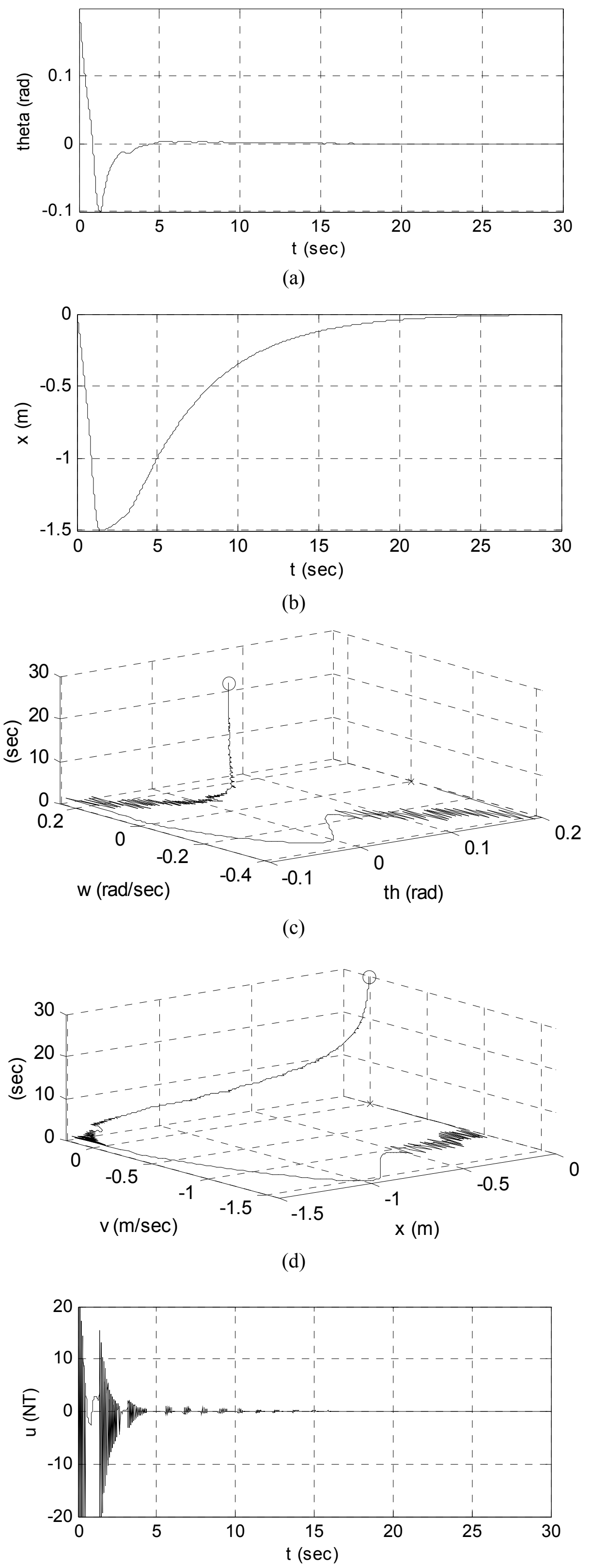

Fig. 6 The control results of a sliding mode controller for 0.2 rad initial condition: (a) The plot of bar moving angle, (b) The plot of carriage moving condition, (c) The phase plane of bar moving condition ('x' is the initial point, 'o' is the final point), (d) The phase plane of carriage moving condition ('x' is the initial point, 'o' is the final point), (e) The control efforts

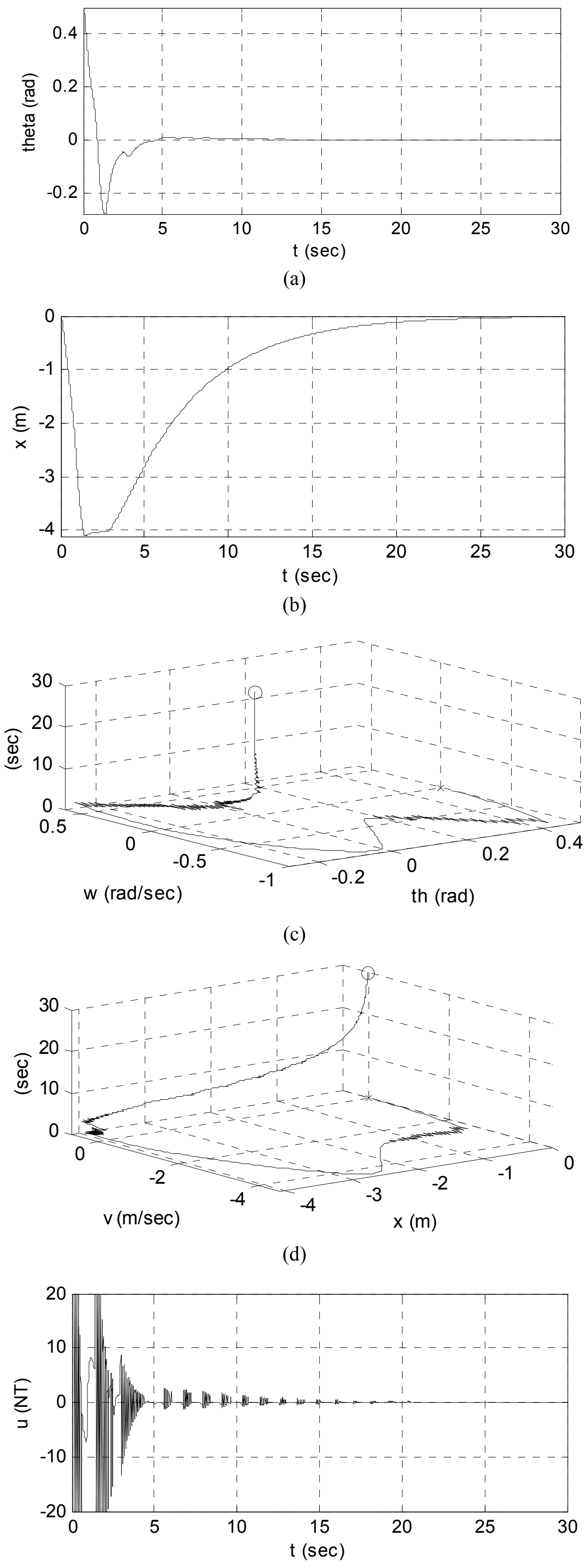

Fig. 7 The control results of a sliding mode controller for 0.5 rad initial condition: (a) The plot of bar moving angle, (b) The plot of carriage moving condition, (c) The phase plane of bar moving condition ('x' is the initial point, 'o' is the final point), (d) The phase plane of carriage moving condition ('x' is the initial point, 'o' is the final point), (e) The control efforts

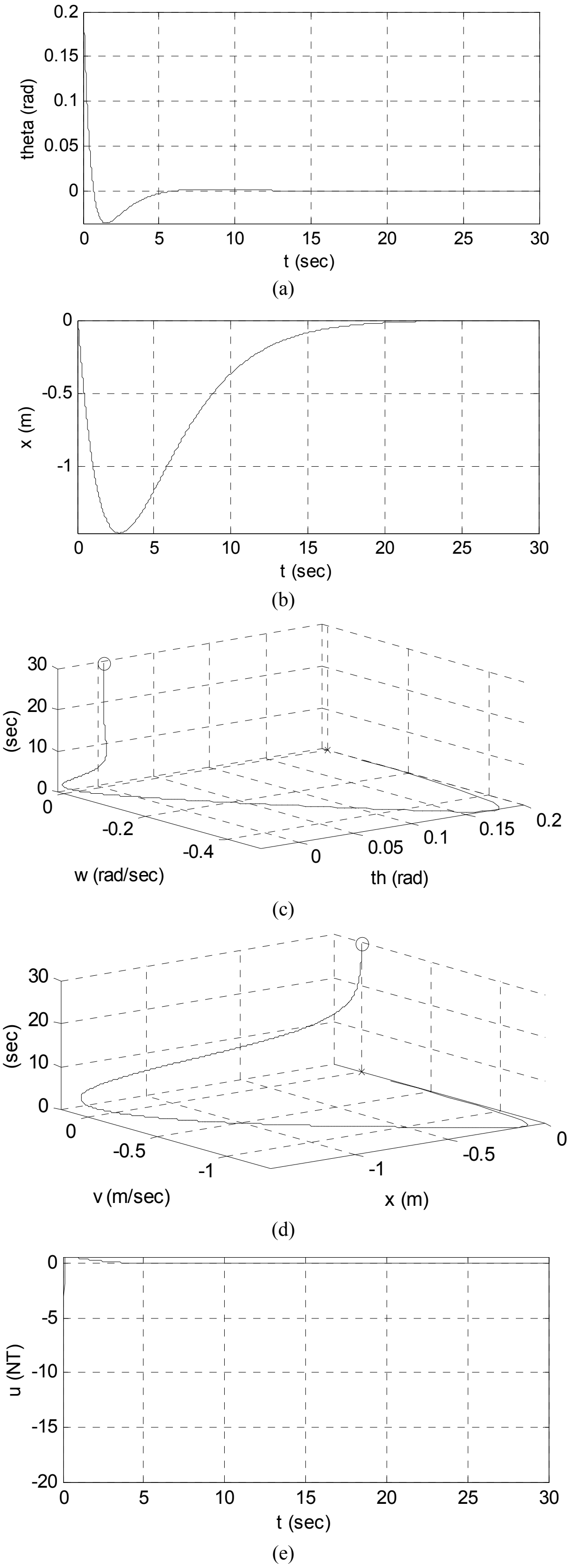

Fig. 8 The control results of the proposed scheme for 0.2 rad initial condition: (a) The plot of bar moving angle, (b) The plot of carriage moving condition, (c) The phase plane of bar moving condition ('x' is the initial point, 'o' is the final point), (d) The phase plane of carriage moving condition ('x' is the initial point, 'o' is the final point), (e) The control efforts

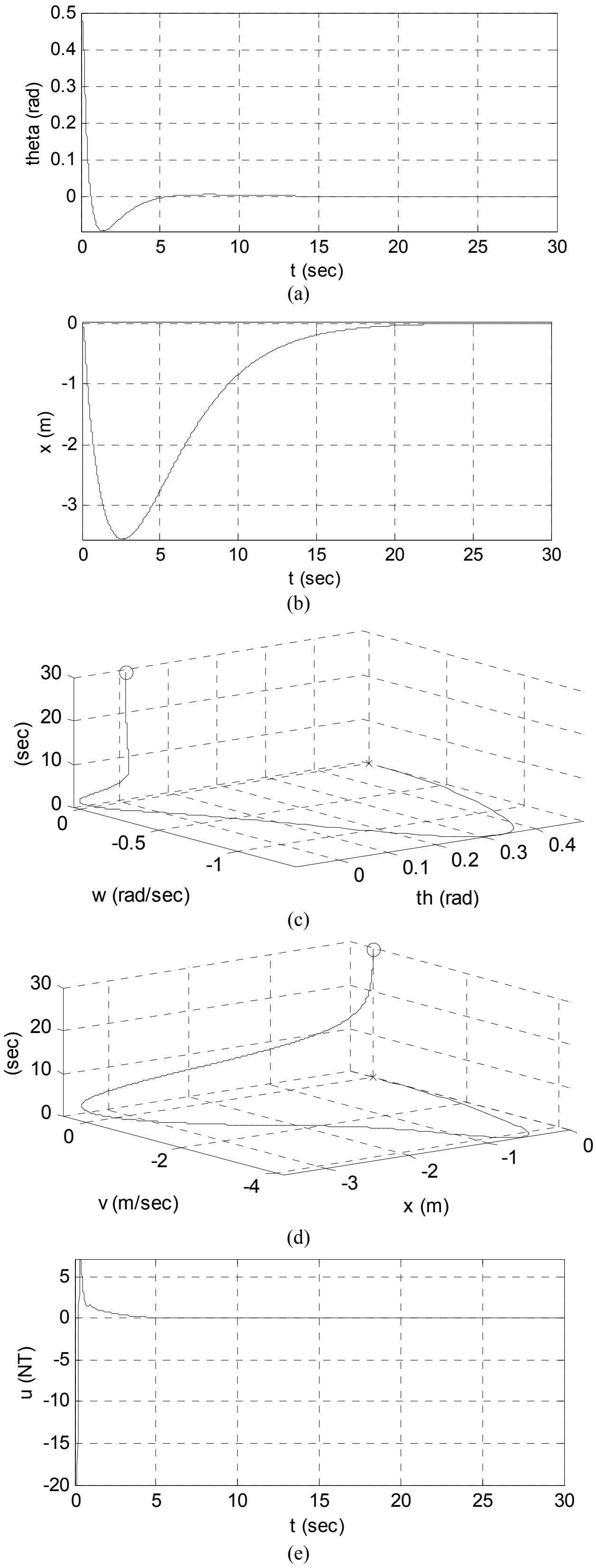

Fig. 9 The control results of the proposed scheme for 0.5 rad initial condition: (a) The plot of bar moving angle, (b) The plot of carriage moving condition, (c) The phase plane of bar moving condition ('x' is the initial point, 'o' is the final point), (d) The phase plane of carriage moving condition ('x' is the initial point, 'o' is the final point), (e) The control efforts

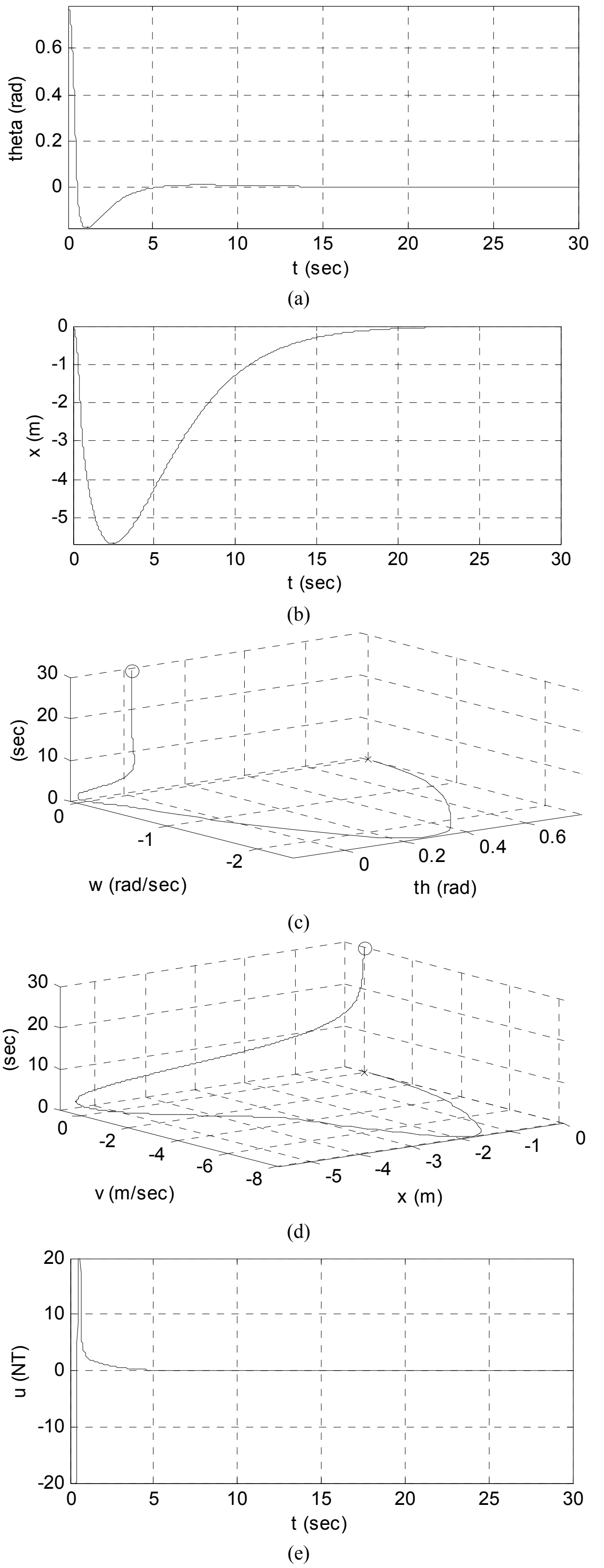

Fig. 10 The control results of the proposed scheme for large offset 0.785 rad: (a) The plot of bar moving angle, (b) The plot of carriage moving condition, (c) The phase plane of bar moving condition ('x' is the initial point, 'o' is the final point), (d) The phase plane of carriage moving condition ('x' is the initial point, 'o' is the final point), (e) The control efforts

2. The proposed scheme can overcome the various perturbations efficiently for its specified intuitively robust and smooth control structure.

3. The proposed scheme designed in a normalized phase plane is suitable to be masked as a servo chip for applications in future.

In summary, the primary work has provided to the control of an inverted pendulum successfully. Most importantly, it also provides another control topics for inverted pendulum systems and further research is thus worthy of being explored.

REFERENCES

[1] C. S. Liu, Y. W. Wang and J. S. Chen, "A normalized smoothing control scheme of a robot manipulator based on fuzzy modeling," *Proceedings of the NSC - Part A: Physical Science and Engineering*, vol. 20, no. 4, pp. 426-438, 1996.

[2] M. Margaliot and G. Langholz, "Adaptive fuzzy controller design via fuzzy lyapunov synthesis," *Proceedings of FUZZ-IEEE'98*, pp. 354-359, 1998.

[3] D. Saez and A. Cipriano, "Design of fuzzy model based predictive controllers and its application to an inverted pendulum," *Proceedings of FUZZ-IEEE'97*, vol. 2, pp. 915-919, 1997.

[4] J. Yi and N. Yubazaki, "Stabilization fuzzy control of inverted pendulum systems," *Artificial Intelligence in Engineering*, vol. 14, pp. 153-163, 2000.

[5] Qifeng Wei, W. P. Dayawansa and W. S. Levine, "Nonlinear controller for an inverted pendulum having restricted travel," *Automatica*, vol. 31, pp. 841-850, 1995.

[6] A. Shiriaev, H. Pogromsky, H. Ludvigsen and O. Egeland, "On global properties of passivity-based control of an inverted pendulum," *International Journal of Robust and Nonlinear Control*, vol. 10, pp. 283-300, 2000.

[7] Y. H. Chang, J. B. Joo and G. C. Park, "Design of robust fuzzy-model-based controller with application to inverted pendulum tracking control," *Proc. of Int'l Tech. Conf. on Circ. Sys. Comput. Commun.* ITC-CSCC'98, pp. 1621-1624, 1998.

[8] L. K. Wong, Frank H. F. Leung and Peter K. S. Tam, "A fuzzy sliding controller for nonlinear systems," *IEEE Transactions on Industrial Electronics*, vol. 48, no. 1, pp. 32-37, Feb. 2001.

[9] V. I. Utkin, "Variable structure systems with sliding modes," *IEEE Transactions on Automatic Control*, vol. 22, pp. 212-222, Apr. 1977.

[10] R. A. DeCarlo, S. H. Zak and G. P. Matthews, "Variable structure control of nonlinear multivariable systems: a tutorial," *Proc. IEEE*, vol. 76, pp. 212-232, Mar. 1988.

[11] S. Lin and Y. Chen, "Design of adaptive fuzzy sliding mode for nonlinear system control," *Proceedings of FUZZ-IEEE'94*, vol. 1, pp. 35-39, 1994

[12] HR. Bereji, "A reinforcement learning-based architecture for fuzzy logic control," *International Journal of Approximate Reasoning*, vol. 1, pp. 267-292, 1992.

[13] H. Lu, S. Tzeng and M. Yeh, "Fuzzy logic controller design using genetic algorithm," *Proceedings of IIZUKA'96*, vol. 2, pp. 525-528, 1996.

[14] A. Ishigame, T. Furukawa, S. Kawamoto and T. Taniguchi, "Sliding mode controller design based on fuzzy inference for nonlinear systems," *IEEE Trans. on Industrial Electronics*, vol. 40, pp. 64-70, 1993.

[15] Y. S. Lu and J. S. Chen, "A self-organising fuzzy sliding mode controller design for a class of nonlinear servo systems," *IEEE Trans. on Industrial Electronics*, vol. 41, pp. 492-502, 1994.

[16] Michio Sugeno and Tanaka Kazuo, "Successive identification of a fuzzy model and its applications to prediction of a complex system," *Fuzzy Sets and Systems*, vol. 42, pp. 315-344, 1991.

[17] Samuel M. Smith and J. Comer David, "Automated calibration of a fuzzy logic controller using a cell state space algorithm," *IEEE Control Systems Magazine*, vol. 11, pp. 18-28, 1991.