A ROBUST ADAPTIVE FUZZY CONTROLLER FOR A CLASS OF NON AFFINE SYSTEMS

N. Essounbouli, A. Hamzaoui, K. Guesmi and J. Zaytoon

Centre de Recherche en STIC
IUT de Troyes
9, rue de Quebec B.P. 396
10026 Troyes cedex – France
Corresponding authors : n.essounbouli@iut-troyes.univ-reims.fr

Abstract: In this paper, a robust adaptive fuzzy controller for non affine-in-control systems subject to external disturbances is presented. Firstly, a Takagi-Sugeno system is used to construct a fuzzy affine-in-control model. Then, an adaptive algorithm is used to adjust the parameter vector and hence to accurate the approximation level. The proposed approach guarantees that the system output tracks a given bounded reference trajectory, the tracking errors converges to a small variable neighbourhood of zero, and the closed loop system is robust despite the presence of external disturbances thanks to H∞ technique. A simulation example is presented to evaluate the performances of the proposed approach

Key Words Takagi-Sugeno Fuzzy Systems, Robust Control, H∞ Technique, Non Affine Systems

I. INTRODUCTION

In recent years, controller design for systems having complex nonlinear dynamics is being an important and challenging topic. Based on the advances in geometric nonlinear control theory, feedback linearization has been widely used [KAH, 96]. However, they can be used only in the case of the exact knowledge of the plant nonlinearities. In order to relax some of the exact model-matching restrictions, several adaptive schemes have recently been used to solve this problem [JAN, 96] [KAN, 91] [KAN, 92] [MAR, 93a] [MAR, 93b].
According to the universal approximation theorem [WAN, 94], many important adaptive fuzzy-based control schemes have been developed to incorporate the expert information directly and systematically, and various stable performance criteria are guaranteed by theoretical analysis [MAR, 95] [SPO, 96] [WAN, 96]. The major advantages in all these fuzzy-based control schemes are that the developed controllers can be implemented without any precise knowledge about the structure of the entire dynamic model. Based on the same idea some adaptive schemes using neural networks and wavelet have been presented in the literature [LEU, 99] [POL, 92] [CHE, 98]. However, the influence of both fuzzy logic approximation errors and the external disturbances can not be eliminated with these approaches. In this sense, several robust adaptive fuzzy controller using the H∞ technique has been developed [BOU, 01] [CHA, 01] [CHE, 96] [ESS, 02a] [ESS, 02b] [HAM, 02]. These approaches are based on adding an H∞ control signal to attenuate the effects of both the external disturbances and the approximation errors to a prescribed level. Other techniques combining sliding mode control and adaptive fuzzy algorithms are also presented in the literature [LIN, 02] [MAN, 03] [WANG, 97] [YOO, 98]. However, all these approaches can be used only in the case of affine-in-control process. To overcome this constraint, some methods based on the decomposition of the fuzzy system to sub-systems to deduce the control law have been presented in the literature [YOO, 01] [BOU, 03]. These approaches are based on adding a control signal to ensure the stability of the closed loop system in Lyapunov sense. However, only the disturbances free systems are treated and some assumptions on the upper bounds of the approximation errors must be satisfied.
In this paper, we propose to synthesise a robust adaptive fuzzy controller for a non affine-in-control process (Fig.1). Indeed, based on a specific formulation of a Takagi-Sugeno (TS) fuzzy system with singleton conclusion, the feedback controller is constructed. To obtain good approximation level, an adaptation law is used for tuning on-line the conclusion part of fuzzy system. To ensure the robustness of the closed loop system and to attenuate the effects of the external disturbances and the approximation errors, an H∞ signal is introduced in the control law. The global stability of the closed loop system is studied used the Lyapunov theory. To evaluate the performances of the proposed controller, a simulation example is presented.

II. PROBLEM STATEMENT

Consider a single-input single-output (SISO) nonlinear system:

$$y^{(n)} = f\left(y, y^{(1)}, \dots, y^{(n-1)}, u\right) + d \qquad (1)$$

where $y \in \Re$ is the measured output, $u \in \Re$ the control input, $y^{(i)}\left(i = 1, 2, \dots, n\right)$ the i-th time derivatives of the output y, and $f(.): \Re^{n+1} \to \Re$ is an unknown nonlinear function.
If we note the state vector as follows $x = \left[x_1, \dots, x_n\right]^T = \left[y, y^{(1)}, \dots, y^{(n-1)}\right]^T$, the system can be represented in the state space by:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 \\ &\vdots \\ \dot{x}_n &= f(x,u) + d \\ x &= y \end{aligned} \qquad (2)$$

The aim is to synthesise a control law allowing to force the output of the system y to track a bounded reference

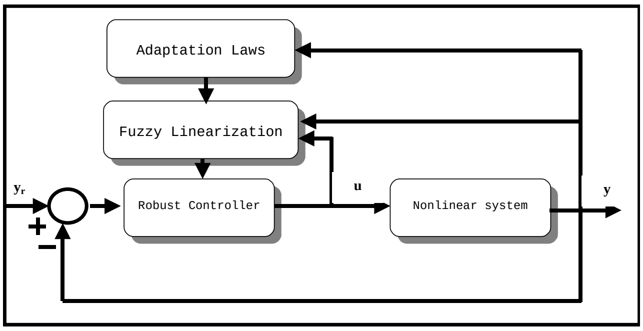

Fig. 1. Control scheme of the proposed controller

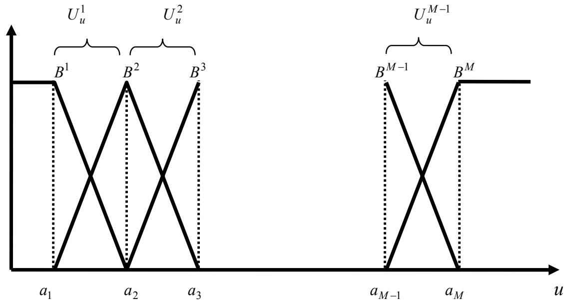

Fig. 2. Membership functions of u

trajectory y_r, and to guarantee the robustness of the closed loop system. In the case where the system is affine, on can use the input-output linearization to obtain a direct and simple relation between the system output and the control input, which allows to use some robust controllers for uncertain and disturbed systems developed in the literature. To overcome the Linearisation problem, we propose to use a TS fuzzy system to approximate the unknown the function $f(.)$. Based on a specific representation of the fuzzy system, we can obtain an affine control description of the plant.

III. FUZZY REPRESENTATION

Takagi-Sugeno (TS) Fuzzy systems have been widely used in the literature due to: i) the numerical value of its conclusion part, which allows to establish the stability analysis and to use some kinds of conventional control theory [HAM, 04] [ESS, 03] [WAN, 97]; ii) it was demonstrated in the literature that the fuzzy systems are universal approximators: a fuzzy system can approximate any nonlinear continuous function on a compact set to an arbitrary accuracy level [WAN, 94].

Based on the previous arguments, we use a TS fuzzy system to approximate the unknown function $f(.)$, which can be constructed from a collection of fuzzy rules with singleton conclusion in the form:

$(j_1, j_2, \ldots, j_n, m)$ the rule :

$$IF\ x_1\ is\ A_1^{j_1}\ And\ x_2\ is\ A_2^{j_2}\ And \ldots And\ x_n\ is\ A_n^{j_n}\ And\ u\ is\ B^m$$
$$THEN\ \ \dot{x}_n = \theta^{(j_1, j_2, \ldots, j_n, m)} \tag{3}$$

where

$j_i \in \{1,2,\ldots, p_i\}$, $\quad i \in \{1,2,\ldots,n\}$, $\quad m \in \{1,2,\ldots, M\}$

$A_i^{j_i} \in T(x_i) = \{A_i^1, A_i^2, \ldots, A_i^{p_i}\}$, $\quad B^m \in T(u) = \{B^1, B^2, \ldots, B^m\}$.

p_i and M represent respectively the number of the fuzzy sets of the state variable x_i and u respectively.

The index j_i of $A_i^{j_i}$ in (3) denotes the j_i^{th} element of the set $T(x_i)$, $\theta^{(j_1, j_2, \ldots, j_n, m)}$ is a parameter to be determined.

Using the singleton fuzzifier, the centre average defuzzification and the product inference engine, the output of the TS fuzzy model (3) is given by [WAN, 94]:

$$\dot{x}_n = \frac{\sum_{j_1=1}^{p_1} \cdots \sum_{j_n=1}^{p_n} \theta^{(j_1, j_2, \ldots, j_n, m)} \left[\left(\prod_{i=1}^{n} \mu_{A_i^{j_i}}(x_i)\right) \mu_{B^m}(u)\right]}{\sum_{j_1=1}^{p_1} \cdots \sum_{j_n=1}^{p_n} \sum_{m=1}^{M} \left[\left(\prod_{i=1}^{n} \mu_{A_i^{j_i}}(x_i)\right) \mu_{B^m}(u)\right]}$$
$$= \hat{f}(x, u, \theta) = \Theta^T \Psi(x, u) \tag{7}$$

where $\Psi(x,u)$ is a $p_1 \times p_2 \times \ldots \times p_n \times M$ dimensional vector with its $(j_1, j_2, \ldots, j_n, m)$ element given by:

$$\Psi^{(j_1, j_2, \ldots, j_n, m)}(x, u) = \frac{\left(\prod_{i=1}^{n} \mu_{A_i^{j_i}}(x_i)\right) \mu_{B^m}(u)}{\sum_{j_1=1}^{p_1} \cdots \sum_{j_n=1}^{p_n} \sum_{m=1}^{M} \left[\left(\prod_{i=1}^{n} \mu_{A_i^{j_i}}(x_i)\right) \mu_{B^m}(u)\right]} \tag{8}$$

and $\Theta = \left[\theta^{(1,1,\ldots,1,1)}, \ldots, \theta^{(p_1, p_2, \ldots, p_n, M)}\right]^T \in \Re^{p_1 \times p_2 \times \ldots \times p_n \times M}$.

The membership functions of linguistic variables of u have the form of a triangle and are placed evenly throughout the whole defined space U_u as illustrated in Fig. 2.

The space U_u can be decomposed into several subspaces $U_u^\alpha (\alpha = 1,2,\ldots, M-1)$. If u exists in subspace U_u^α, all membership functions of linguistic variable of u are given by:

$$\mu_{B^m}(u) = \begin{cases} \dfrac{u - a_{m+1}}{a_m - a_{m+1}} & m = \alpha \\ \dfrac{a_{m-1} - u}{a_{m-1} - a_m} & m = \alpha + 1 \\ 0 & otherwise \end{cases} \tag{9}$$

where a_m is a constant satisfying $\mu_{B^m}(a_m) = 1$.

Substituting (9) in (7) and considering that u exists in subspace U_u^α, we obtain:

$$\hat{f}^\alpha(x, u, \theta) = \frac{1}{a_\alpha - a_{\alpha+1}} \sum_{j_1=1}^{p_1} \cdots \sum_{j_n=1}^{p_n} \xi^{(j_1, j_2, \ldots, j_n)}(x) \left(a_\alpha \theta^{(j_1, j_2, \ldots, j_n, \alpha+1)} - a_{\alpha+1} \theta^{(j_1, j_2, \ldots, j_n, \alpha)}\right)$$
$$+ \frac{1}{a_\alpha - a_{\alpha+1}} \sum_{j_1=1}^{p_1} \cdots \sum_{j_n=1}^{p_n} \xi^{(j_1, j_2, \ldots, j_n)}(x) \left(\theta^{(j_1, j_2, \ldots, j_n, \alpha)} - \theta^{(j_1, j_2, \ldots, j_n, \alpha+1)}\right) u$$
$$= \phi_1^\alpha(x, \Theta) + \phi_2^\alpha(x, \Theta) u \tag{10}$$

where $\xi^{(j_1,j_2,\dots,j_n)}(x)=\dfrac{\prod_{i=1}^{n}\mu_{A_i^{j_i}}(x_i)}{\sum_{j_1=1}^{p_1}\cdots\sum_{j_n=1}^{p_n}\left[\left(\prod_{i=1}^{n}\mu_{A_i^{j_i}}(x_i)\right)\mu_{B^m}(u)\right]}$

Therefore, the fuzzy system can be decomposed into M-1 subsystems, which allows obtaining an affine-in-control structure [LI, 97] [LI, 99].

VI. Robust adaptive fuzzy controller design

After have defining a canonical model, given by (10), based on the fuzzy system decomposition, our task in this section is to synthesise a suitable control law, which allows to guarantee the good tracking performances and the robustness of the closed loop system. To attain this objective, we propose the following control law:

$$u=\frac{1}{\phi_2^{\alpha}(x,\Theta)}\left[-\phi_1^{\alpha}(x,\Theta)+\underline{k}^T\underline{e}+y_r^{(n)}-u_s\right] \tag{11}$$

where $\underline{k}=[k_1,\dots,k_n]^T$ is the feedback gain vector calculated such that the corresponding polynomial is asymptotically stable, $y_r^{(n)}$ is n^{th} time derivative of the reference trajectory, and $\underline{e}^T=\left[e,\dots,e^{(n-1)}\right]=\left[y_r-y,\dots,(y_r-y)^{(n-1)}\right]$ the tracking error vector. The term u_s denotes the additional signal guaranteeing the robustness of the closed system by attenuating the effects of both the external disturbances and the approximation errors to a prescribed level.

Using equations (2) and (11), the dynamic error can be given by:

$$\begin{aligned}e^{(n)}&=\phi_1^{\alpha}(x,\Theta)+\phi_2^{\alpha}(x,\Theta)u-\underline{k}^T\underline{e}+u_s-f(x,u)-d\\&=\hat f(x,u,\Theta)-f(x,u)-\underline{k}^T\underline{e}+u_s-d\end{aligned} \tag{12}$$

which can be written as:

$$e^{(n)}=\hat f(x,u,\Theta)-\hat f^*(x,u,\Theta^*)-\underline{k}^T\underline{e}+u_s-d+w_f \tag{13}$$

where $\hat f^*(x,u,\Theta^*)$ is the optimal value of $\hat f(x,u,\Theta)$, and $w_f=\hat f^*(x,u,\Theta^*)-f(x,u)$.

The dynamic error equation (13) can be reformulated as:

$$\dot{\underline{e}}=A\underline{e}+B\left[\tilde\Theta^T\Psi(x,u)+u_s+w\right] \tag{14}$$

with $\tilde\Theta=\Theta-\Theta^*$, $w=w_f-d$,

$$A=\begin{bmatrix}0&1&0&\cdots&0\\0&0&1&\cdots&0\\\cdots&\cdots&\cdots&\cdots&\cdots\\-k_1&-k_2&-k_3&\cdots&-k_n\end{bmatrix},\ B=\begin{bmatrix}0\\0\\\vdots\\1\end{bmatrix}.$$

A is a stable matrix, thus it can be associated with the following algebraic Riccati equation which has a unique symmetric positive definite solution, P, if and only if $\frac{2}{r}-\frac{1}{\rho^2}\ge 0$, i.e., if $2\rho^2\ge$ r:

$$AP^T+PA+Q-2PB\left(\frac{1}{r}-\frac{1}{2\rho^2}\right)B^TP=0 \tag{15}$$

where Q is a positive definite matrix given by the designer, r a positive constant and ρ the attenuation level.

To synthesise the adaptation law of the adjustable parameter vector Θ and the additional control signal u_s, we consider the following Lyapunov equation:

$$V=\frac{1}{2}\underline{e}^TP\underline{e}+\frac{1}{2\gamma}\tilde\Theta^T\tilde\Theta \tag{16}$$

with γ is a positive constant.

The differentiation of (16) along (14) gives

$$\begin{aligned}\dot V=&\frac{1}{2}\underline{e}^T\left[A^TP+PA\right]\underline{e}+\underline{e}^TPB\left[\tilde\Theta^T\Psi(x,u)+u_s+w\right]\\&+\frac{1}{\gamma}\tilde\Theta^T\dot{\tilde\Theta}\end{aligned} \tag{17}$$

Using the Riccati equation (15) and the fact that $\dot{\tilde\Theta}=\dot\Theta$ yields

$$\begin{aligned}\dot V=&-\frac{1}{2}\underline{e}^TQ\underline{e}+\underline{e}^TPB\left[\frac{1}{r}B^TP\underline{e}+u_s+w-\frac{1}{2\rho^2}B^TP\underline{e}\right]\\&+\frac{1}{\gamma}\tilde\Theta^T\left[\dot\Theta+\gamma\underline{e}^TPB\,\Psi(x,u)\right]\end{aligned} \tag{18}$$

if we chose the following control signal

$$u_s=-\frac{1}{r}B^TP\underline{e} \tag{19}$$

and the following adaptation law for updating on-line the parameter vector Θ

$$\dot\Theta=-\gamma\underline{e}^TPB\,\Psi(x,u) \tag{20}$$

then equation (18) becomes

$$\dot V=-\frac{1}{2}\underline{e}^TQ\underline{e}+\underline{e}^TPB\left[w-\frac{1}{2\rho^2}B^TP\underline{e}\right] \tag{21}$$

After some manipulations, we can write

$$\dot V=\frac{-1}{2}\underline{e}^TQ\underline{e}-\frac{1}{2}\left(\frac{B^TP\underline{e}}{\rho}-\rho w\right)^2+\frac{\rho^2}{2}w^2 \tag{22}$$

Since the term $\left(\frac{B^TP\underline{e}}{\rho}-\rho w\right)^2$ is positive, we have

$$\dot V\le\frac{-1}{2}\underline{e}^TQ\underline{e}+\frac{\rho^2}{2}w^2 \tag{23}$$

Integrating the above inequality from t=0 to the system response time τ, and after some simplification we can obtain the following H∞ criterion:

$$\frac{1}{2}\int_0^{\tau}\underline{e}^TQ\underline{e}\,dt\le V(0)+\frac{\rho^2}{2}\int_0^{\tau}w^2\,dt \tag{24}$$

Then the proposed approach allows to ensure the convergence of the tracking error toward a closed value despite the presence of both (bounded) external disturbances and approximation errors.

Remark:

i) In the case where we have enough information about the dynamic behaviour of the plant, we can use them to improve the convergence of the adaptive algorithm as illustrated in [ESS, 02a]. Indeed, these information are used to obtain the initial values of the adjustable parameters, which allows to attain quickly their optimal values.

ii) Generally, the ranges of the state variables are well-known. Hence, based on (2), we can have the maximal value of the dynamic function $f(x,u)$. This allows to use the projection algorithm given in [ESS, 02a] to guarantee the convergence of the adaptive algorithm despite the arbitrary choice of the initial value of the adjustable parameters.

V. SIMULATION EXAMPLE

An example is used to illustrate the effectiveness of the proposed adaptive controller for unknown non affine nonlinear systems. Consider the following nonlinear plant [YOO, 01]:

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = x_1^2 + 0.15u^3 + 0.1\left(1 + x_2^2\right)u + \mathbf{sin}(0.1u) + d$$

It appears clearly that this nonlinear system is non affine-in-control. In this case, the proposed approach can be used. The control objective is to design a controller so that the closed loop system output y follows the desired trajectory: $y_r(t) = \mathbf{sin}(t)$ and the closed lop system is robust despite the presence of external disturbances assumed in the form $d(t) = 0.5\,\mathbf{sin(}t\mathbf{)} + 0.5\,\mathbf{cos(}2t\mathbf{)}$. The initial state is $x(0)$ = [0.6,0.5]. The universe of discourse of the inputs x_1, x_2 and u are respectively $[-2.5\ 2.5]$, $[-2.5\ 2.5]$ and $[-6\ \ 6]$. For each variable, we have defined respectively 5, 5 and 6 linguistic sets.
To synthesise the feedback controller, we choose, k_1=2, k_2=1 and Q=diag(10,10). Furthermore to simplify the calculation, we choose $r = 2\rho^2$ and ρ=0.2.
The figures 2 and 3 gives the evolution of the state variables x_1 and x_2 together with the corresponding reference signals. One can note the good tracking performances and the convergence of the system to the desired trajectories as illustrated on figure 4. This can be justified by the good approximation level assured by the adaptive algorithm as shown in figure 5. The applied control signal to attain our objective is given by figure 6.
Comparing the obtained results with those presented in [YOO, 01] [BOU, 03], we remark that the proposed approach guarantees better tracking performances despite the presence of external disturbances in our case.

6. CONCLUSION

In this work, a robust adaptive fuzzy controller applied to non affine nonlinear systems was presented. To exploit the feedback linearisation technique, a Takagi-Sugeno fuzzy system is used to approximate the system model. The numeric nature of its conclusion part allows us to construct an affine-in-control fuzzy model of the studied plant. In order to increase the approximation level, an adaptation algorithm is adopted to adjust on-line the parameter vector of the fuzzy system. The robustness of the closed loop system is assured by an additional control signal deduced from the H∞ technique. To show the efficiency of the proposed approach, a benchmark example was presented.

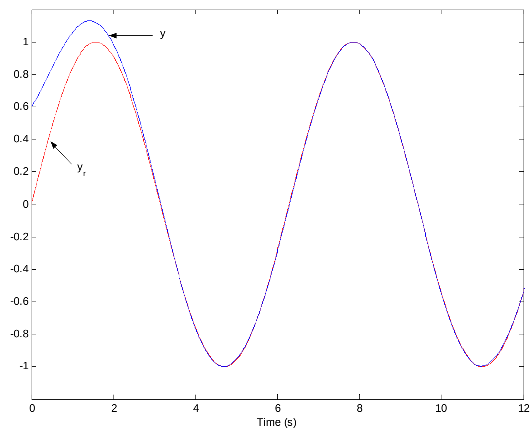

Figure 2: System output with corresponding reference signal

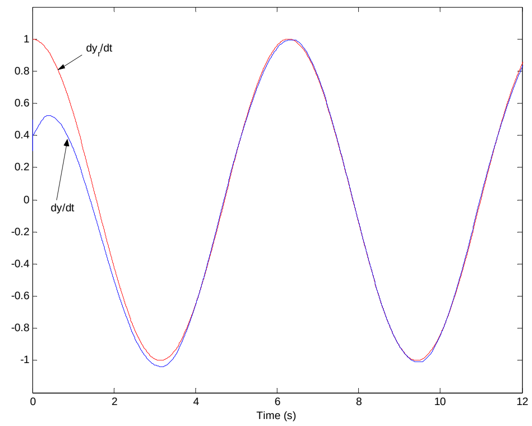

Figure 3: State variable dy/dt with corresponding reference signal

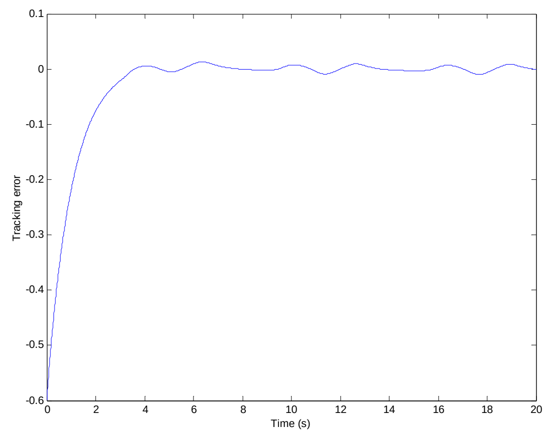

Figure 4: Tracking error

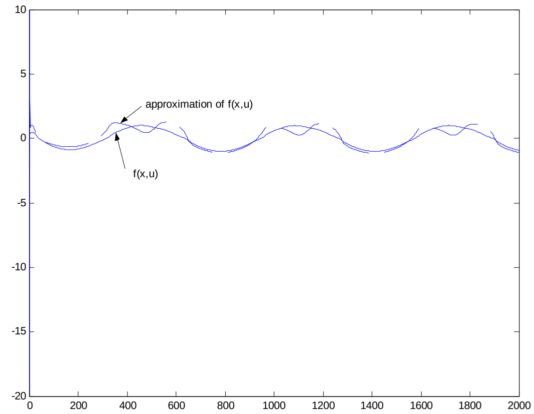

Figure 5: Evolution of the nominal function $f(x,u)$ and its approximation

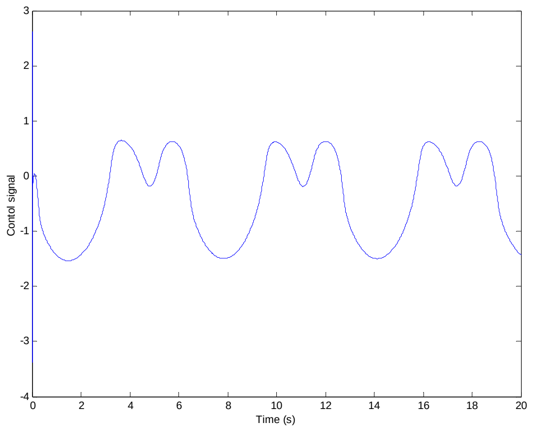

Figure 6: Control input signal

REFERENCES

[BOU, 01] Boukezzoula, R., S. Galichet and L. Foulloy (2001) Robust Fuzzy Control for a Class of Nonlinear Systems Using Input-Output Linearizasion: Real-Time Implementation for a Robot Wrist. In Proc. of IEEE Inter. Conf. On Control Aplications, pp. 311-316, Mexico City, Mexico.

[BOU, 03] Boukezzoula, R., S. Galichet and L. Foulloy (2003) Fuzzy adaptive linearizing control for non-affine systems. In Proc. of IEEE Inter. Fuzzy Syst. Conf, pp. 543-548, St Louis, MO, USA.

[CHA, 01] Chang, Y.-C (2001). Adaptive fuzzy-based tracking control for nonlinear SISO systems via VSS and H∞ approaches. IEEE Trans. on Fuzzy Syst. Vol. 9, pp 278-292.

[CHE, 96] Chen, B-S., C-H. Lee and Y-C. Chang (1996). H∞ tracking design of uncertain nonlinear SISO systems: Adaptive fuzzy approaches, IEEE Trans. Fuzzy Syst., Vol. 4, no. 1, pp. 32–43.

[CHE, 98] Cheng, Y.M., B.S. Chen, and F.Y. Shiau (1998) Adaptive Wavelet Network Control Design for Nonlinear Systems, Proc. of the National Science Concil, Rep. of China, Par A: Physical Science and Engineering, vol. 22, pp. 783-799.

[HAM, 02] Hamzaoui, A., A. Elkari and J. Zaytoon (2002). Robust adaptive fuzzy control application to uncertain nonlinear systems in robotics, Journal of Systems and Control Engineering, Vol. 216, Part 1,pp.225-235.

[HAM, 04] Hamzaoui A., Essounbouli N., and Zaytoon J. (2004) Fuzzy sliding mode control with a fuzzy switching function for non-linear uncertain multi-input multi-output systems, Jour. Syst. and Contr. Engineering, vol. 218, part. 1, pp. 287-297.

[ESS, 02a] Essounbouli, N., A. Hamzaoui and J. Zaytoon (2002a). A supervisory robust adaptive fuzzy controller. In Proc. of 15th IFAC World Congress on Automatic and Control, Barcelona, Spain.

[ESS, 02b] Essounbouli, N., A. Hamzaoui, K. Benmahammed and J. Zaytoon (2002b). A robust adaptive fuzzy control applied to disturbed MIMO systems. In Proc. of IEEE Conference on Control Applications, Glasgow, Scotland.

[ESS, 03] Essounbouli N., Hamzaoui A. and Benmahammed K. (2003) Adaptation Algorithm for Robust Fuzzy Controller of Nonlinear Uncertain Systems, In Proc. of IEEE Conference on Control Applications, Istanbul, Turkey, pp. 386-391.

[JAN, 96] Jankovic M. (1996) Adaptive output feedback control of nonlinear feedback linearizable system. lnt. J. Cont. Vol. 10, pp. 1-18.

[KAN, 91] Kanellakopoulos, I., P. V. Kokotovic, and A. S. Morse. (1991) Systematic design of adaptive controller for feedback linearizable systems. IEEE Trans. On Autom. Contr., Vol. 36, pp. 1241-1253.

[KAN, 92] Kanellakopoulos, I., P. V. Kokotovic, and A. S. Morse. (1992) Adaptive output feedback control of systems with output nonlinearities," IEEE Trans. On Autom. Contr., Vol. 37, pp. 1166-1182.

[KHA, 96] Khalil, H.K. (1996). Adaptive output feedback control of nonlinear system represented by input-output models. IEEE Trans. on Autom. Contr. Vol. 41, pp 177-188.

[LEU, 99] Leu, Y.G., W.Y. Wang, T.T. Lee (1999) Robust adaptive fuzzy-neural controller for uncertain nonlinear systems, IEEE Trans. Robotics Automat,.Vol. 15, pp. 805–817.

[LI, 97] Li H.X., Gatland H.B., and Green A.W. (1997) Fuzzy variable structure control", IEEE Trans. on Systems, Man, and Cybernetics, Part B, vol. 27, no. 2, pp. 306-312.

[LI, 99] Li H.X., and Tso S.K. (1999) Higher order fuzzy control structure for higher order or time-delay systems, IEEE Trans. on Fuzzy Systems, vol. 7, no. 5, pp. 540-552, 1999.

[LIN, 02] Lin W.S. and Chen C.S. (2002) Robust Adaptive Sliding Mode Control using Fuzzy Modeling for a Class of Uncertain MIMO Nonlinear Systems, IEE Proceedings on Control Theory Applications, vol. 149, pp. 193-202.

[MAN, 03] Manamanni N., Hamzaoui A. and Essounbouli N. (2003) Sliding Mode Control with Adaptive Fuzzy Approximator for MIMO Uncertain Systems″, Proc. of European Control Conference ECC'03, Cambridge, UK, 2003.

[MAR, 93a] Marino, R., and P. Tomei (1993a) Global adaptive output-feedback control of nonlinear systems, part I: Linear parameterization," IEEE Trans. On Autom. Contr., Vol.. 38, pp. 17-32.

[MAR, 93b] Marino, R., and P. Tomei (1993b) Global adaptive output-feedback control of nonlinear systems, part II: Linear parameterization," IEEE Trans. On Autom. Contr., Vol.. 38, pp. 33-48.

[MAR, 95] Marino, R., and P. Tomei (1995). Nonlinear control design: Geometric, Adaptive and Robust. Englewood Cliffs, NJ: Prentice Hall.

[POL, 92] Polycarpou, M. and P.A. loannou (1992) Modelling, identification and stable adaptive control of continuous-time nonlinear dynamical systems using neural networks. In Proc. of Amer. Control Conf., Chicago, IL, pp. 36–40.

[SPO, 96] Spooner, J.T., and K.M. Passino (1996). Stable adaptive control using fuzzy systems and neural networks. IEEE Trans. on Fuzzy Syst. Vol. 4, pp

[TEE, 91] Teel, A., R. Kadiyala, P. V. Kokotovic, and S. S. Sastry (1991) Indirect techniques for adaptive input output linearization of nonlinear systems. lnt. J. Contr., Vol. 53, pp. 193-222.

[WAN, 94] Wang L.X. (1994) Adaptive Fuzzy Systems and Control, Englewood Cliffs, New Jersey: Prentice-Hall, 1994.

[WAN, 96] Wang L.-X. (1996) Stable Adaptive Fuzzy Controllers with application to Inverted Pendulum Tracking, IEEE Trans. on Systems, Man and Cybernetics, vol. 26, pp. 677-691, 1996.

[WAN, 97] Wang L.X. (1997) A course in Fuzzy Systems and Control, Prentice-Hall PTR, Upper Saddle River, New Jersey, 1997.

[YOO, 98] Yoo B. and Ham W. (1998) Adaptive Fuzzy Sliding Mode Control of Nonlinear System″, IEEE Trans. on Fuzzy System, vol. 6, pp. 315-321.

[YOO, 01] Yoon, P.-S., J.-H. Park and G.-T. Park (2001) Adaptive fuzzy control of nonaffine nonlinear systems using Takagi6Sugeno models. In Proc. of IEEE Inter. Fuzzy Syst. Conf, pp. 642-645, Melbourne, Australia.