FUZZY ADAPTIVE CONTROL DESIGN FOR TRACKING ERROR REDUCTION IN NONLINEAR SYSTEMS

[1]T.SIVANAGARAJU , [2]K.RAJASEKHAR
[1]M.TECH student, [2]ASSISTANT PROFESSOR
Electronics and Communication Engineering
University college of engineering/JNTUK, JNTU Kakinada,E.Gdist, A.P,India,533003

Abstract: This paper presents adaptive fuzzy controller for nonlinear systems with nonaffine function. The objective of design of the controller is to reduce the tracking error to a minimum level and ultimate boundness of all the internal signals. Dynamic surface controller (DSC) is used to design the controller, this technique eliminates the explosion of complexity in the backstepping technique. Estimation of nonlinear system function reduces the tracking error, in this paper fuzzy logic system (FLS) is used to estimate the nonlinear system function for better accuracy than neural network system (NNW) .

Index terms: Adaptive control, DSC, FLS, NNW, tracking error.

I. INTRODUCTION

A nonlinear system is a system in which the change of the output is not proportional to the change of the input and the system don't obey the superposition theorem. State-space representation of the pure feedback nonlinear system is shown below.

$$\dot{x}_i = h_i(\vec{x}_i, x_{i+1}) + \Delta_i(t), \text{where i=1,2,....n-1.}$$
$$\dot{x}_n = h_n(x, u) + \Delta_n(t) \qquad (1)$$
$$y = x_1$$

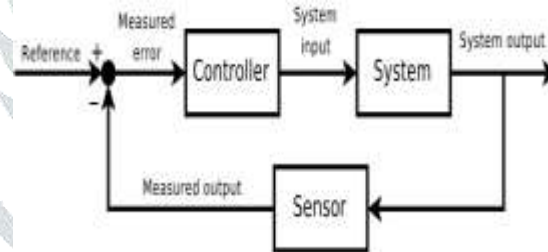The general closed loop system block diagram is shown below.

Figure 1.0

The main objective of the closed loop system is to generate the controlling system and apply to the plant so that the system output should fallow or track the reference signal. The system tracking accuracy improves when the tracking error (difference between the reference signal and measured plant output) becomes as low as possible. So the main objective of this paper shows the tracking error can further reduce by using fuzzy logic controller instead of neural network based system [1].

For past decade, Research has been made on NNW or FLS approximation based adaptive controllers design for nonlinear systems control. These approximators provide accurate approximation of nonlinear functions in the system with minor knowledge about the system. Robust control techniques are to suppress or compensate the error caused by the uncertainties.so the robust compensation techniques combined with approximation based adaptive control technique solve the most of the problems in the controlling of nonlinear system.

This paper is different from the other papers

1) the controller is designed using dynamic surface control (DSC) technique [5] instead of backstepping technique [2] which eliminates the "problem of complexity".

2) Differentiable condition on the nonaffine function w.r.t to controlling signal is removed because of this it allows this technique can be applied to more practical systems[6]-[11][14][15].

3) It uses fuzzy logic system instead of neural networks for tracking error reduction [1][11][13].

II. DYNAMIC SURFACE CONTROL (DSC):

There are different techniques to design the controller for nonlinear system some of them are feedback linearization, backstepping technique, multiple sliding surface (MSS) control etc. The backstepping technique is a recursive type structure, the design process start at the known stable system and backout new controller that progressively stabilize each outer system. The process terminates when the final external control is reached. But this technique suffers with the problem of "explosion of complexity".

To overcome this problem and to increase the robustness of the designed controller motivates new controller design technique like MSS (the combination of the basic procedure of the backstepping technique and some robust controlling techniques).

DSC is a novel technique that removes the problem of "explosion of complexity". This technique is different from the MSS is it uses the low pass filter to generate the desired sliding surface. The below figure 2.0 shows the general structure of the DSC system.
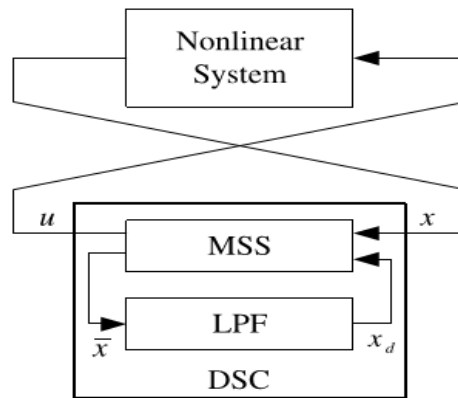

Figure 2.0

The DSC controller designed for the nonlinear system shown in the eq (1) is

$$\bar{x}_2 = \dot{x}_{1d} - h_1(x_1) - M_1 D_1 \qquad (2)$$

$$\bar{x}_3 = \dot{x}_{2d} - h_2(x_1, x_2) - M_2 D_2 \qquad (3)$$

$$\bar{x}_i = \dot{x}_{(i-1)d} - h_{i-1}(x_1, x_2, .., x_{i-1}) - M_{i-1} D_{i-1} \qquad (4)$$

$$u = \dot{x}_{nd} - h_n(x_1, x_2, ..., x_n) - M_n D_n \qquad (5)$$

LPF is

$$\tau_2 \dot{x}_{2d} + x_{2d} = \bar{x}_2, \; x_{2d}(0) = \bar{x}_2(0) \quad (6)$$

$$\tau_i \dot{x}_{id} + x_{id} = \bar{x}_i, \; x_{id}(0) = \bar{x}_i(0) \qquad (7)$$

error surfaces are

$$D_1 = x_1 - y_d,$$

$$D_2 = x_2 - x_{2d},$$

$$\ldots$$

$$D_n = x_n - x_{nd}$$

III.   FUZZY LOGIC SYSTEM (FLS):

Fuzzy logic system is based on the IF-Then rules. Fuzzy logic system uses fuzzy member ship functions to map the input variables. The process of converting crisp input value to fuzzy value is called fuzzification. Defuzzification is an opposite process to fuzzification which is a process of converting different fuzzy values into a crisp value as output. Different membership functions are available for fuzzification and defuzzification example triangular, trapezoidal, Gaussian distribution etc.

if FLS with fallowing if-then rules Ri: If x_1 is F_{1i} and.... and x_n is F_{ni} Then y is B_i

Then output of FLS with center of sums method defuzzifier is formulated as

$$y(x) = \frac{\sum\limits_{i=1}^{N} \psi_i \prod\limits_{j=1}^{n} \mu_{Fji}(x_j)}{\sum\limits_{i=1}^{N} \prod\limits_{j=1}^{n} \mu_{Fji}(x_j)} \qquad (8)$$

where x=[$x_1, x_2, \ldots x_n$].$\in R^n$, $\psi_i = \max\limits_{y \in R} \mu_{Bi}(y)$

$\mu_{Fji}(x_j)$, $\mu_{Bi}(y)$ are the membership functions of F_{ji} and B_i respectively.

$$\text{Let } \xi_i(x) = \frac{\prod_{j=1}^{n} \mu_{Fji}(x_j)}{\sum_{i=1}^{N} \prod_{j=1}^{n} \mu_{Fji}(x_j)} \quad (9)$$

$\xi(x) = [\xi_1(x), \xi_2(x)......\xi_N(x)]$, and $\psi = [\psi_1, \psi_2, ...\psi_N]^T$

Then the fuzzy logic system can be rewritten as fallows

$$y(x) = \psi^T \xi(x) \qquad (10)$$

IV. DESIGN OF ADAPTIVE FUZZY CONTROLLER:
Problem statement :

Consider a non-affine pure feedback nonlinear system

$$\dot{x}_i = h_i(\vec{x}_i, x_{i+1}) + \Delta_i(t), \text{where i=1,2,....n-1.}$$

$$\dot{x}_n = h_n(x, u) + \Delta_n(t)$$

$$y = x_1$$

Where x=[x₁, x₂, ….xₙ] , are the system n states, $\vec{x}_i = [x_1, x_2, ...x_i]$

u is the controlling input to the system and
y is output of the system,
h(.) is the unknown nonlinear function which specify the system functionality.
$\Delta(t)$ is the uncertainty or disturbance comes from external which is unknown.

Objective is to design an adaptive controller that gives the controlling signal to the system so that the system output fallows the reference signal. Here we cannot use the conventional controller like PID or feedback linearize controllers because the system we are considering is a nonlinear system.

Adaptive fuzzy controller:

The design of adaptive fuzzy controller [4] for the system in (1) is

$$D_1 = x_1 - y_d,$$

$$D_i = x_i - x_{id} \quad \text{where } 2 \leq i \leq n$$

And the x_{id} is obtained from the LPF

$$\tau_i \dot{x}_{id} + x_{id} = \bar{x}_i,$$

The controller equations obtained using DSC technique is modified to implement the adaptive controller. The resultant virtual control laws are

$$\bar{x}_{i+1} = -M_i D_i - \frac{\hat{\varphi}_i D_i}{2c_i^2} \xi^T_i(\vec{x}_i)\xi_i(\vec{x}_i)$$

$$- \beta_i \dot{x}_{id} \tanh(\frac{D_i \dot{x}_{id}}{\zeta_i}) - \hat{\delta}_i \tanh(\frac{D_i}{\zeta_i}) \qquad (11)$$

where $1 \leq i \leq n-1$,

$$u = \bar{x}_{i+1} = -M_i D_i - \frac{\hat{\varphi}_i D_i}{2c_i^2} \xi^T_i(\vec{x}_i)\xi_i(\vec{x}_i)$$

$$- \beta_i \dot{x}_{id} \tanh(\frac{D_i \dot{x}_{id}}{\zeta_i}) - \hat{\delta}_i \tanh(\frac{D_i}{\zeta_i}) \qquad (12)$$

when u is the actual control law.
Corresponding adaptive laws are

$$\dot{\hat{\varphi}}_i = \frac{\kappa_i D_i^2}{2c_i^2} \xi_i^T(\vec{x}_i)\xi_i(\vec{x}_i) - \sigma_i \kappa_i \hat{\varphi}_i \quad (13)$$

$$\dot{\hat{\delta}}_i = \gamma_i D_i \tanh(\frac{D_i}{\zeta_i}) - \sigma_i \gamma_i \hat{\delta}_i \quad (14)$$

Where i=1, 2...n

γ_i, σ_i, κ_i, ζ_i, c_i^2, M_i are design parameter can be varied depending on the plant.

$\xi_i(\vec{x}_i)$ Is defined in the equation (2) where $\vec{x}_i = [x_1, x_2, \ldots x_i]$

Stability analysis of the closed loop system is proved using lyapunova stability theorem [1].

V.   SIMULATIONS AND RESULTS:

Consider the fallowing non affine pure feedback system

$$\dot{x}_1 = x_1 + x_2 + \frac{x_2^3}{5} + 0.2\sin(t)$$

$$\dot{x}_2 = x_1 x_2 + \phi(u) + 0.1\cos(t)$$

$$y = x_1$$

The nonaffine function is non-differentiable w.r.t u is given as

$$\phi(u) = \begin{vmatrix} (u-1.5) + \dfrac{(u-1.5)^3}{7} & u \geq 1.5 \\ 0 & -2.5 < u < 1.5 \\ (u+2.5) + \dfrac{(u+2.5)^3}{7} & u \leq -2.5 \end{vmatrix}$$

Reference signal is generated using van der pol oscillator model described as follows

$$\dot{x}_{r1} = x_{r2}$$

$$\dot{x}_{r2} = -x_{r1} + 0.2(1 - x_{r1}^2)x_{r2}$$

$$y_r = x_{d1}$$

The adaptive controller is designed based on the
equations (11) and (12) gives the virtual control law and actual controller law.
Equation (13) and (14) gives the adaptive laws.
LPF is designed based on the equation (6 & 7).
FLS is designed based on the equation (9).
The required design parameters are shown in the table1.

Table 1.0

Design Parameter	Value
σ_1, σ_2	0.02,0.02
κ_1,κ_2	3,3
ζ_1, ζ_2	0.75,0.75
B_1,β_2	2,1
c_1,c_2	0.15,0.15
M_1,M_2	2,4
γ_1, γ_2	2,2
τ_2	0.05

Gaussian membership function parameters of FLS are shown in table 2

Table 2.0

Center	a_{1i}= 2, 1, 0,-1,-2
	a_{2i}=0.5,0.25,0,-0.25,0.5
Variance	v_1=2, v_2=2

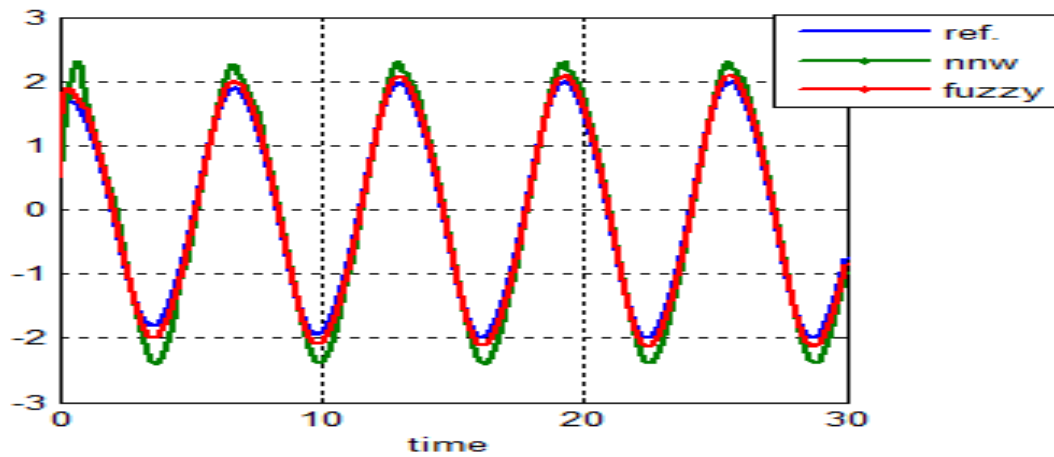All the simulations are carried in the Simulink and the results are shown in the below figures.

Figure 3.0

Figure 3.0 shows the system output for the NNW based adaptive control [1] and FLS based adaptive controller for the same input reference signal.
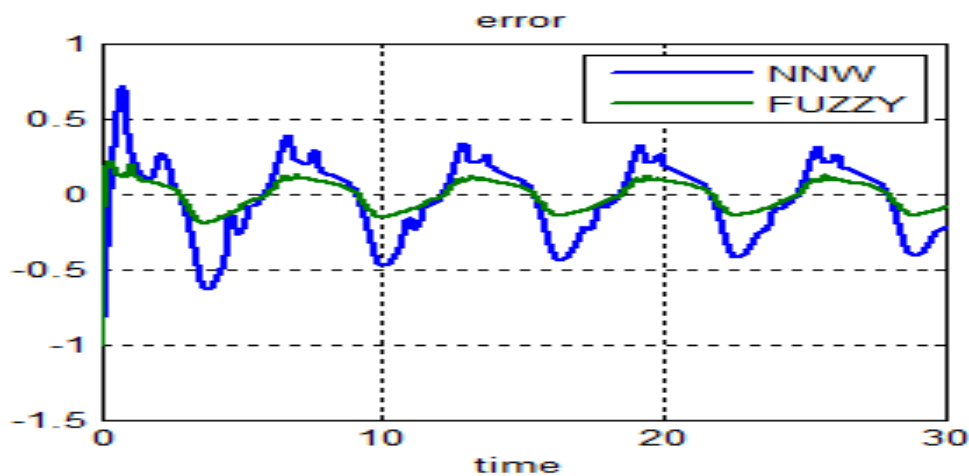

Figure 4.0

Figure 4.0 shows the comparison of measured tracking error at every instant between NNW &FLS based adaptive controller. This figure clearly shows that the tracking or fallow error is reduced by using FLS .based adaptive controller in nonlinear system control compared to the NNW based adaptive control.
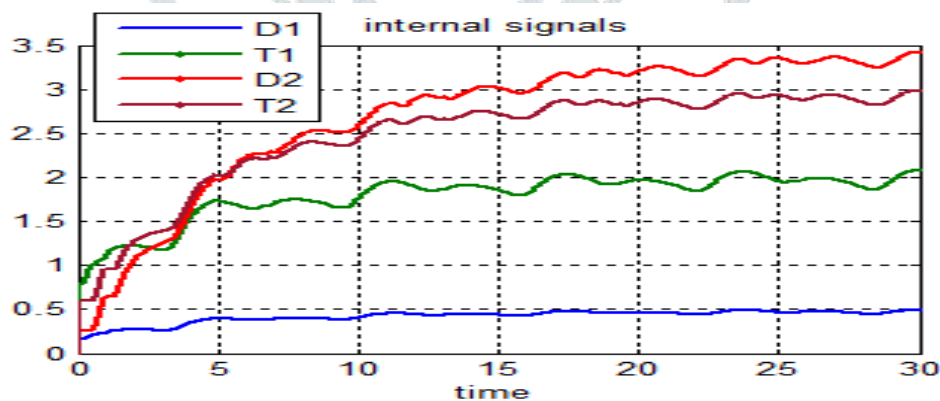

Figure 5.0

Figure 5.0 shows the values of the internal signals that are always bounded to a finite value.so that the system is stable at infinite time.

VI.   CONCLUSION

This paper showed that the tracking error in nonlinear system reduced further by using fuzzy logic based adaptive control system using DSC technique compared with the NNW based technique. The tracking error can further reduce and the system fallow accuracy can be improved by using a neuro-fuzzy controller.

References :

[1]   Z. C. Liu, X. M. Dong, J. P. Xue, H. B. Li, and Y. Chen, "Adaptive neural control for a class of pure-feedback nonlinear systems via dynamic surface technique," *IEEE Trans. Neural Netw. Learning Syst.*, vol. 27, no.9, pp. 1969-1975, Sep. 2016.

[2]   T. Zhang, S. S. Ge, and C. C. Huang, "Adaptive neural network control for strict-feedback nonlinear systems using backstepping design," *Automatica*, vol. 36, no. 12, pp. 1835-1846, Dec. 2000.

[3]   Y. M. Li, S. C. Tong, Y. J. Liu, and T. S. Li, "Adaptive fuzzy robust output feedback control of nonlinear systems with unknown dead zones based on a small-gain approach," *IEEE Trans. Fuzzy Syst.*, vol. 22, no.1, pp. 164-176, Feb. 2014.

[4]   A. M. Zou, Z. G. Hou, and M. Tan, "Adaptive control of a class of nonlinear pure-feedback systems using fuzzy backstepping approach," *IEEE Trans. Fuzzy Syst.*, vol. 16, no. 4, pp. 886-897, Aug. 2008.

[5]   P. P. Yip, "Adaptive dynamic surface control: A simplified algorithm for adaptive backstepping control of nonlinear systems," *Int. J. Control*, vol.71, no. 5, pp. 959C979, 1998.

[6]   G. Sun, D. Wang, and Z. Peng, "Adaptive control based on single neural network approximation for non-linear pure-feedback systems," *IETControl Theory Appl.*, vol. 6, no. 15, pp. 2387-2396, Dec. 2012.

[7]   W. Meng, Q. Yang and etc., "Adaptive neural control of high-order uncertain nonaffine systems: A transformation to affine systems approach,"*Automatica*, vol. 50, no. 2, pp. 1473-1480, Apr. 2014.

[8]   Z. Chen, S. S. Ge, Y. Zhang, and Y. Li, "Adaptive neural control of MIMO nonlinear systems with a block-triangular pure-feedback control structure," *IEEE Trans. Neural Netw.Learning Syst.*, vol. 25, no. 11, pp.2017-2029, Nov. 2014.

[9]   H. Du, H. Shao, and P. J. Yao, "Adaptive neural network control for a class of low-triangular-structured nonlinear systems," *IEEE Trans. Neural Netw.*, vol. 17, no. 2, pp. 509-514, May. 2006.

[10]   S. J. Yoo, "Adaptive control of non-linearly parameterized pure-feedback systems," *IET Control Theory Appl.*, vol. 6, no. 3, pp. 467-473, Mar. 2012.

[11]   D. Wang, and J. Huang, "Adaptive neural network control for a class of uncertain nonlinear systems in pure-feedback form," *Automatica*, vol.38, no. 1, pp. 1365-1372, Jan. 2014.

[12]   R. M. Sanner and J.-J. E. Slotine, "Gaussian networks for direct adaptive control," *IEEE Trans. Neural Netw.*, vol. 3, no. 6,pp. 837–863, Nov. 1992.

[13]   T. Zhang and S. S. Ge, "Adaptive neural network tracking control of MIMO nonlinear systems with unknown dead zones and control directions," *IEEE Trans. Neural Netw.*, vol. 20, no. 3, pp. 483–496, Mar. 2009.

[14]   Z. C. Liu, X. M. Dong, J. P. Xue, and L. P. Zhang, "Adaptive tracking control for nonlinear systems with a class of input nonlinearities," *Asian J. Control*, vol. 18, no. 2, pp. 771-778, Jan. 2016.

[15]   Z. C. Liu, X. M. Dong, J. P. Xue, and Y. Chen, "Adaptive neural control for a class of time-delay systems in the presence of backlash or dead-zone nonlinearity," *IET Control Theory Appl.*, vol. 8, no. 11, pp. 1009-1022,Jul. 2014.

[16]   Y. Wen and X. Ren, "Neural networks-based adaptive control for nonlinear time-varying delays systems with unknown control direction,"*IEEE Trans. Neural Netw.*, vol. 22, no. 10, pp. 1599–1612, Oct. 2011.

[17]   "Stability Analysis of Nonlinear Systems Using Lyapunov Theory" ,lecture by Dr. RadhakantPadhi,Professor,Dept. of Aerospace Engineering,IISc – Bangalore.

[18] AnamikaVyas Ojha1, Achala Khandelwal2 "control of nonlinear system using backsteping", IJRET, Volume: 04 Issue: 05 | May-2015

[19]   J. K. Hedrick, P. P. Yip," Multiple Sliding Surface ControlTheory and Application", 588/Vol. 122, DECEMBER 2000,Transactions of the ASME, Journal of Dynamic Systems, measurement, and Control.

[20]   B. Song, J.K. Hedrick, "Dynamic Surface Control of Uncertain Nonlinear Systems",Communications and Control Engineering,DOI 10.1007/978-0-85729-632-0_2, © Springer-Verlag London Limited 2011

[21]   Neural networks and fuzzy systems-kosko.B, Prentice-Hall of India Pvt Ltd.1994

[22]   Introduction to fuzzy control-Driankov,Hellendroom,Narosa Publishers

[23]   Adaptive Control design and analysis,GangTao,copy right@2003 Jhon Wiley &sons,Inc.