Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

# Sensor Fault Compensation for Nonlinear Systems Using Fuzzy Adaptive Sliding Control

**Yingwei Zhang* and S. Joe Qin****

**Key Laboratory of Integrated Automation of Process Industry, Ministry of Education, Northeastern University, Shenyang, Liaoning 110004, P. R. China (zhangyingwei@ise.neu.edu.cn)*
*** The Mork Family Department of Chemical Engineering and Materials Science, Ming Hsieh Department of Electrical Engineering, Daniel J. Epstein Department of Industrial and Systems Engineering, University of Southern California, 925 Bloom Walk, HED 210, Los Angeles, CA 90089-121190(email:sqin @usc.edu)*

**Abstract:** An active sensor fault compensation control law is developed for a class of nonlinear systems to guarantee the closed-loop stability in the presence of a fault, based on a fuzzy logic system and sliding mode. Through the adaptive process of the parameters, the dynamics caused by the fault is counteracted. The fuzzy sliding mode control is introduced to attenuate the fuzzy approximation error. Simultaneously, the closed-loop system is stable in Lyapunov sense and the tracking error converges to a neighbourhood of zero. The example of the proposed design indicates that the fault compensation control law is effective for a nonlinear system.

## 1. INTRODUCTION

In the past decades, people are faced with more complex systems when the performance requirements increase. Actuator, sensor or component faults drastically change the complex system behavior. Therefore, it is necessary to improve reliability of a system by diagnosing faults of individual components and applying fault-tolerant control (FTC) systems [1-20].

Within the category of the passive fault-tolerant controls, reliable control is widely used. Results and scheme details can be found in [5-7]. Robust control design is often adopted for reliable control to have the guaranteed closed-loop stability and $H_\infty$ performance. This type control is typically conservative, without controller adjustment after detection of a fault; the tolerance comes at the cost to the control performance.

In an active fault-tolerant control, faults are accommodated, typically by a reconfiguration of the feedback control law. An excellent overview on the subject has been given by [8]. Faults are typically associated with sensors and actuators failures; in correspondence, respective tolerant strategies can be so designed. Different methods for dealing with the reconfiguration problem have been reported. Most of them adopt the following methods: neural networks [33], fuzzy logic systems [7], adaptive control [22], [23], [31], eigenstructure assignment [24], Markov model [32], multiple-model tracking [25], [26], and compensation via additive input design [27], [28], [29]. In particular, an excellent overview of the fault accommodation has been discussed in [30]. Most fault compensation applied the neural networks to accommodate the faults. However, It is difficult for the Neural networks to attenuate the approximation errors. The sensor fault compensation strategy based on both fuzzy logic system and sliding mode controller for nonlinear systems is provided for the first time in this paper. In our design, Also, the fuzzy sliding mode control is introduced to attenuate the fuzzy approximation error. The closed-loop system is simultaneously stable in Lyapunove sense.

Sliding mode control, due to its robustness against modeling imprecisions and external disturbances, has been successfully employed to the fault-tolerant control. Some existed references utilize the sliding mode and the Lyapunov function syntheses approach to design globally stable controllers in case of the presence of a fault. However, some of them are limited to nonlinear systems with constant control gain; or the convergence of the tracking error depends on the assumption that the error is square integrable; or the control scheme depends on the assumptions to make the parameters matched completely, which may not be easy to check or realize. In this article, the fault compensation strategy based on both fuzzy logic system and sliding mode controller for nonlinear systems for first time is proposed for the first time in this article. We adopt a stable fuzzy adaptive controller through sliding mode control and weakened the above restrictive conditions. It utilizes the properties of the linguistic variables that fuzzy control itself possesses, adopts inference approach to substitute the discontinuous parts in the sliding mode and to make the control signal smooth. Thus, fuzzy sliding mode control has an exact mathematical expression which can attenuate the chattering phenomenon being inherent to the conventional sliding mode controller.

The remainder of the paper is organized as follows. The

978-1-1234-7890-2/08/$20.00 © 2008 IFAC

10.3182/20080706-5-KR-1001.0548

problem statement and its assumptions are given in Section 2, followed by the formulation of our controller and its relevant proofs in Section 3. An illustrative example is given in Section 4 to demonstrate the effectiveness of the proposed method. Finally, conclusions are drawn in Section 5.

## 2. PROBLEM STATEMENTS

Consider a system described as:

$$\dot{x} = a(x) + \sum_{i=1}^{p} b_i(x)u_i \qquad y_i = c_i(x), \quad (i = 1,2,\cdots,p) \tag{1}$$

where $x \in R^n, y, u \in R^p$ are the state, output and input of the system, respectively.

$a(x) \in R^n$, $b_i(x) \in R^n$, $c(x) = [c_1(x), \ \cdots, c_p(x)]^T \in R^p$.

Definition 1 system (1) has uniform strong relative degree vector $[r_1,\cdots,r_p]^T$ if for all integer $m_i < r_i - 1$ and $\forall x \in R^n$, the following equations is held

$$L_{b_i} L_a^{m_i} c_i(x) = 0, \tag{2}$$

$$L_{b_i} L_a^{r_i-1} c_i(x) \neq 0, \ (i = 1,2,\cdots,p) \tag{3}$$

Assumption 1 System (1) has uniform strong relative degree vector $[r_1,\cdots,r_p]^T$ for $\forall x \in R^n$.

From Assumption 1, there exists differential coefficient homeomorphism [34]

$$(\xi,\eta) = T(x) \tag{4}$$

such that

$$\begin{aligned} &\dot{\xi}_{i1} = \xi_{i2} \\ &\dot{\xi}_{i2} = \xi_{i3} \\ &\cdots \\ &\dot{\xi}_{i(r_i-1)} = \xi_{ir_i} \\ &\dot{\xi}_{ir_i} = \zeta_i(\xi,\eta) + g_i(\xi,\eta)u_i = \zeta_i(x) + g_i(x)u_i \\ &y_i = \xi_{i1} + \beta(t-T_i)f_i(x) \end{aligned} \tag{5}$$

where

$$\begin{aligned} &\zeta_i(x) = L_a^{r_i} c_i(x) = \zeta_i(\xi,\eta) \\ &\zeta(x) = (\zeta_1^T(x),\cdots,\zeta_p^T(x))^T \\ &g_i(x) = L_b L_a^{r_i-1} c_i(x) = g_i(\xi,\eta), \\ &g(x) = (g_1^T(x),\cdots,g_p^T(x))^T \\ &\xi_i = (\xi_{i1},\xi_{i2},\cdots\xi_{ir_i})^T \end{aligned} \tag{6}$$

where $f = (f_1, f_2, \cdots, f_p)^T$ is sensor fault function. $\eta_i \in R^{n-r}$ is a diffeomorfism on $R^n$ and the $\eta_i$ dynamics, which are referred to as the "internal dynamics", can be expressed as follows:

$$\dot{\eta}_i = q_i(\xi_i,\eta_i) = q_i(x) \tag{7}$$

$f$ characterizes the changes in the dynamics due to the actuator failure, where $T$ is the actuator fault occurrence time (determined by the fault diagnosis). The nonlinear fault function $f$ is multiplied by a switching function $\beta(t-T)$,

$$\beta(t-T) = diag\ (\beta(t-T_1), \beta(t-T_2), \cdots, \beta(t-T_p)) \tag{8}$$

where

$$\beta(t-T_i) = \begin{cases} 0 & \text{if } t < T_i \\ 1 & \text{if } t \geq T_i \end{cases}, \ i = 1,2,\cdots,p\ ,. \tag{9}$$

The system (1) without the fault occurrence is called "normal system".

Assumption 2 $g(x)$ is bounded away from singularity over a compact set $S \subset R^n$, specifically

$$\|g(x)\|^2 = tr(g^T(x)g(x)) \geq b > 0 \tag{10}$$

where $b$ represents the smallest singular value of the matrix $g(x)$.

Let $y_{im}$ as the reference input, assume $y_{im}, \dot{y}_{im}, \cdots, y_{im}^{(r)}$ are all bounded and measurable. Define the tracking error as

The sliding mode control is based on a notational simplification, which amounts to replacing a high order tracking problem by a first order stabilization problem. Although "perfect" performance can in principle be achieved in the presence of arbitrary parameter inaccuracies. In some applications where control chattering is acceptable, the control can yield extremely high performance (Slotine 1991). The aim of a sliding controller is to

(i) Design a control law to effectively account for
parameter uncertainty, e.g. imprecision on the mass properties or loads, inaccuracies on the torque constants of the actuators, friction, and so on.
the presence of unmodeled dynamics, such as structural resonant models, neglected time-delays ( in the actuators, for instance), or finite sampling rate.
(ii) Quantify the effect on tracking performance of discarding any particular term in the dynamic model.

$$e_i(t) = y_i(t) - y_{im}(t)\ ,\ e = (e_1, e_2, \cdots e_p)^T, \tag{11}$$

$$y_m = (y_{1m}, y_{2m}, \cdots y_{pm})^T \tag{12}$$

The control objective: design the fault-tolerant controller such that

(1) All the variables of the closed-loop systems are bounded.
(2) the tracking error $e(t)$ converges to zero or a neighborhood of zero asymptotically.

## 3. MAIN RESULT

First, the fuzzy logic system of $f(x)$ for adjusting the parameter vector $\hat{\gamma}$ is built as following

$$\hat{f}(x|\gamma) = \hat{\gamma}^T \sigma(x) \tag{13}$$

$\gamma^*$ is the optimal parameter vector of $\gamma$, define $\gamma^*$ to be as follows:

$$\gamma^* = \arg\min_{\gamma\in\Omega}[\sup_{x\in N} \left|\hat{f}(x|\gamma) - f(x)\right|] \tag{14}$$

where $\Omega$ is feasible field of $\gamma$, $N$ is a subspace of $R^r$.
from the lemma 1, there exists the nonnegative function $\varepsilon(x)$ and a constant $\varepsilon$ such that

$$f(x) - \hat{f}(x|\gamma^*) = \varepsilon(x) \tag{15}$$

For the fault, design the controller as following

$$u_N = g^{-1}(x)[-\zeta(x) + K^T e + y_m^{(n)} + \frac{1}{2}\mu s] - ku_b \tag{16}$$

$$u_F = g^{-1}(x)[-\hat{f}(x|\gamma)] \tag{17}$$

where $k = g^{-1}(x)\varepsilon$, $K^T = (k_0, \cdots, k_{n-1})^T$ and the selecting of $K$ satisfies Hurwitz polynomial: $L(s) = s^{(n)} + k_{n-1}s^{(n-1)} + \cdots + k_0$ is Hurwitz polynomial, which roots will lie in the open left half-plane. $u_b = (u_{1b}, \cdots, u_{pb})^T$ is the fuzzy sliding mode controller and is determined as follows:

Define the sliding hyper planes $s_i(t)$ as

$$s_i(t) = (\frac{d}{dt} + \upsilon_i)^{(r-1)} e_i \tag{18}$$

where $\upsilon_i$ is a strictly positive constant.
Design the fuzzy sliding mode controller $u_{ib}$ as follows:
First, define the linguistic description of the $s_i$ and $u_{ib}$ as following:

$$T(s_i) = \{NB, NM, ZR, PM, PB\} = \{C^1, C^2, \cdots, C^5\} \tag{19}$$

$$T(u_{ib}) = \{NB, NM, ZR, PM, PB\} = \{F^1, F^2, \cdots, F^5\} \tag{20}$$

where $NB$, $NM$, $ZR$, $PM$ and $PB$ are labels of fuzzy sets, which express "negative big", "negative medium", "zero", "positive medium" and "positive big". They are take to be triangle-shaped fuzzy sets.

Using intuitive inference, the fuzzy relationship between the tracking error $s_i$ and the controller $u_{ib}$ can be built as:

$$R^j: \text{if } s_i \text{ is } C^j, \text{ then } u_{ib} \text{ is } F^{6-j}, j = 1, 2, \cdots, 5 \tag{21}$$

From the $j$ th rule, it can be obtained that the fuzzy relation is

$$R^j = C^j \times F^{6-j}, \tag{22}$$

$$\text{i.e. } R^j(s_i, u_{ib}) = C^j(s_i) \bigcap F^{6-j}(u_{ib}) \tag{23}$$

therefore, the total fuzzy relation is

$$R = \bigcup_{j=1}^{5} R^j, \tag{24}$$

$$\text{i.e. } R(s_i, u_{ib}) = \bigcup_{j=1}^{5} [C^j(s_i) \bigcap F^{6-j}(u_{ib})] \tag{25}$$

the fuzzy set $F$ can be calculated singleton, max-min fuzzy reasoning:

$$F(u_{ib}) = \bigcup_{j=1}^{5} [C^j(s_i) \bigcap F^{6-j}(u_{ib}) \tag{26}$$

using center-average deffuziffier, we have the control output

$$u_{ib} = \frac{\int_{-\frac{3}{2}}^{\frac{3}{2}} u_{ib} F(u_{ib}) du_{ib}}{\int_{-\frac{3}{2}}^{\frac{3}{2}} F(u_{ib}) du_{ib}} \tag{27}$$

$$u_{ib} = \begin{cases} 1 & z_i \le -1 \\ \dfrac{(2z_i + 3)(3z_i + 1)}{2(4z_i^2 + 6z_i + 1)} & -1 < z_i \le -0.5 \\ \dfrac{z_i(2z_i + 1)}{2(4z_i^2 + 2z_i - 1)} & -0.5 < z_i \le 0 \\ \dfrac{z_i(2z_i - 3)}{2(4z_i^2 - 2z_i - 1)} & -0.5 < z_i \le 1 \\ -1 & z_i > 1 \end{cases} \tag{28}$$

It's mathematical expression was derived [35] as follows

$$u_{ib} = \begin{cases} 1 & z_i \le -1 \\ \dfrac{(2z_i+3)(3z_i+1)}{2(4z_i^2+6z_i+1)} & -1 < z_i \le -0.5 \\ \dfrac{z_i(2z_i+1)}{2(4z_i^2+2z_i-1)} & -0.5 < z_i \le 0 \\ \dfrac{z_i(2z_i-3)}{2(4z_i^2-2z_i-1)} & -0.5 < z_i \le 1 \\ -1 & z_i > 1 \end{cases} \quad (29)$$

where $z_i = \dfrac{s_i}{\varphi_i}$, where $\varphi_i$ is the width of the border layer, when $|s_i| \ge \varphi_i$, it is easy to check

$$u_{ib} = -\operatorname{sgn}(s_i) \quad (30)$$

Choose the adaptive law as follows

$$\dot{\hat{\gamma}} = -\eta_1 e^T PB\sigma(x) \quad (31)$$
$$\dot{\hat{\mu}} = \eta_2 (e^T PB)^2 \quad (32)$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -k_0 & -k_1 & -k_2 & \cdots & -k_{n-1} \end{bmatrix},$$

$$B = \begin{bmatrix} 0 & 0 & \cdots & 1 \end{bmatrix}^T, \quad (33)$$

where $P$ is the positive solution of (34).

$$PA + A^T P = -Q \quad (34)$$

Theorem 1 Consider the system (5), under the assumption 1, adopt the normal controller $u_N$ determined by the equation (21), the fault tolerant controller $u_F$ determined by the equation (22) and the adaptive law (31) and (32), then tracking error converges to a neighborhood of zero.

Proof: choose the sliding hyper plane $s = e^T PB$,

$$\dot{e} = Ae - B[\hat{f}(x|\gamma) - \hat{f}(x|\gamma^*)] + B\frac{\mu^*}{2}s + B\frac{\mu^* - \hat{\mu}}{2}s - Bg(x)ku_b - B[\hat{f}(x|\gamma^*) - f(x)] \quad (35)$$

Let $\tilde{\mu} = \mu^* - \hat{\mu}$ is estimate error, choose the Lyapunov function as following

$$V = e^T Pe + \frac{1}{2\eta_1}\tilde{\gamma}^T\tilde{\gamma} + \frac{1}{2\eta_2}\tilde{\mu}^T\tilde{\mu} \quad (36)$$

taking the derivative of V, yield

$$\begin{aligned} \dot{V} &= \dot{e}^T Pe + e^T P\dot{e} + \frac{1}{2\eta_1}\tilde{\gamma}^T\dot{\tilde{\gamma}} + \frac{1}{2\eta_2}\tilde{\mu}^T\dot{\tilde{\mu}} \\ &= -e^T Qe - 2e^T PB[\tilde{\gamma}^T\sigma(x) - \frac{\tilde{\mu} - \mu^*}{2}s] + \\ &\quad 2e^T PB[\varepsilon(x) - g(x)k \ \operatorname{sgn}(s)] + \frac{1}{\eta_1}\tilde{\gamma}^T\dot{\tilde{\gamma}} + \frac{1}{\eta_2}\tilde{\mu}^T\dot{\tilde{\mu}} \end{aligned} \quad (37)$$

from $s\operatorname{sgn}(s) = |s|$ and the adaptive laws (31) and (32), we have

$$\dot{V} \le -e^T Qe - \mu^*(e^T PB)^2 + 2|e^T PB|[\varepsilon(x) - g(x)k] \quad (38)$$

from the choice of $k$, we obtain $2|e^T PB|[\varepsilon(x) - g(x)k] \le 0$, therefore

$$\begin{aligned} \dot{V} &\le -e^T Qe - \mu^*(e^T PB)^2 \\ &\le -e^T\Gamma e \\ &\le 0 \end{aligned}$$

where $\Gamma = Q + \mu^* PBB^T P$.

Assume $\lambda$ is the minimum eigenvalue of $\Gamma$, then the equation (38) becomes

$$\dot{V} \le -\lambda|e|^2 \le 0 \quad (39)$$

from above, we have $V \in L_\infty$, $e \in L_\infty$.
Integrating (39), yields

$$\int_0^\infty (\lambda|e|^2)dt \le V(0) - V(\infty) \quad (40)$$

rom $\dot{e} \in L_\infty$, $\dfrac{d}{dt}\|e\|_2 = \dfrac{e^T\dot{e}}{\|e\|_2} \le \|\dot{e}\|_2 \in L_\infty$, and by Barbalet lemma, we have $\lim_{t\to\infty} e = 0$.

## 4. EXAMPLE

Consider the system as follows:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ y_1 &= \sin x_2 \\ \dot{x}_2 &= (x_2^2 + 2x_1)\sin(x_2) + [1 + \exp(-x_1)]u \\ y_2 &= \sin x_1 \end{aligned} \quad (41)$$

The given reference output is $y_{im} = 0, i = 1,2$.
Define the close-set as follows

$$A_d = \{(x_1, x_2) : \frac{x_1^2}{4} + \frac{x_2^2}{4} \le 1\}$$
$$A_1 = \{(x_1, x_2) : \frac{x_1^2}{4} + \frac{x_2^2}{4} \le 1 + 0.1\} \quad (42)$$

Employ five fuzzy rules as follows:

$$R^l: \text{ IF } x \text{ is } A^l \text{ THEN } y' \text{ is } B^l,$$
$$l = -2, -1, 0, 1, 2 .$$

Where

$$A^l = \exp\left[-\frac{(x-l)^2}{2}\right], \; l = -2, -1, 0, 1, 2 . \quad (43)$$

Define

$$v_i(x) = \frac{A^i(x)}{\sum_{i=-2}^{2} A^i(x)} \quad (44)$$

then

$$y'(x) = \hat{\gamma}^T v(x) \quad (45)$$

We use the fuzzy logic system to approximate the unknown fault functions (it is added to the plant in $T = 1s$ )

$$f_1(x) = \theta \sin(\frac{\pi}{2} x), \; g_1^{-1}(x) = \frac{1}{1+\exp(-x)} \quad (46)$$

where $\theta \in (-1, 1)$. We take the parameters of the controller with the fault tolerant as follows

$$\eta_1 = 0.5, \eta_2 = 0.9, \; \varphi = 0.5, \; \varepsilon = 2.0 \quad (47)$$

## 5. CONCLUSION

Because it is difficult for the Neural networks to attenuate the approximation errors. The fault compensation strategy based on both fuzzy logic system and sliding mode controller for nonlinear systems is proposed in this paper. In our design, Also, the fuzzy sliding mode control is introduced to attenuate the fuzzy approximation error. The closed-loop system is simultaneously stable in Lyapunove sense.

## REFERENCES

[1] X. Zhang, T. Parisini, M.M. Polycarpou, Adaptive fault-tolerant control of nonlinear uncertain systems: An information-based diagnostic approach, IEEE Trans. Autom. Control, vol. 49, pp. 1259–1274, 2004.
[2] R. Dunia, S. J. Qin, "Subspace approach to multidimensional fault identification and reconstruction," AIChE J., vol. 44, pp. 1813–1831,1998.
[3] S. X. Ding, M. Zhong, T. Jeinsch, and B. Tang, "LMI-based integration of robust H $_\infty$ control and RFD for LTI systems," in Proc. IFAC World Congr., Barcelona, Spain, pp. 494–499, 2002.
[4] S. C. Patwardhan, S. Manuja, S. Narasimhan, S. L. Shah, "From data to diagnosis and control using generalized orthonormal basis filters, Part II: model predictive and fault tolerant control," Journal of Process Control, vol. 16, pp. 157–175, 2006.
[5] N. H. El-Farra, A. Gani, P. D. Christofides, Fault-tolerant control of process systems using communication networks, AIChE J., vol. 51, pp. 1665–1682, 2005.
[6] J. Lee, S. J. Qin, I. Lee, Fault detection and diagnosis based on modified independent component analysis, AIChE J., vol. 52, pp. 3501-3514, 2006.
[7] Y. Zhang, Fuli Wang, Tim Hesketh, D. J. Clements, R. Eaton, Fault accommodation of nonlinear system. I. J. Syst. Sci., vol. 36, no. 4, pp. 215-220, 2005.
[8] G. Tortora, B. Kouvaritakis and D. W. Clarke, "Simultaneous optimization of tracking performance and accommodation of sensor faults," I. J. Control, vol. 75, no. 3, pp: 163-176, 2002.
[9] M. Idan, M. Johnson, J. A. Calise and J. Kaneshge, "Intelligent aerodynamic /propulsion flight control for flight safety: A nonlinear adaptive approach," in Proc. Amer. Contol conf., pp. 2918-2923, 2001.
[10] N. Wu, Y. Zhang, and K. Zhou, "Detection, estimation and accommodation of loss of control effectiveness," Int. J. Adaptive Control Signal Process, vol. 14, pp. 775–795, 2000.
[11] R. J. Veillette, J. V. Medanic, and W. R. Perkins, "Design of reliable control systems," IEEE Trans. Automat. Contr, vol. 37, no. 3, pp. 290–300, 1992.
[12] G. Yang, S. Zhang, J. Lam and J. Wang "Reliable control using redundant controllers," IEEE Trans. Automat. Contr., vol. 47, no. 11, pp. 1558-1593, 1998.
[13] M. Vidyasagar and N. Viswanadham, "Reliable stabilization using a multicontroller configuration," Automatica, vol. 21, no. 5, pp. 599-602,1985.
[14] L. Tan, Dragoslav D. Siljak, and Masao Ikeda,. "Reliable stabilization via factorization methods", IEEE Trans. Automat. Contr., vol. 37, pp. 1786-1791,1991.
[15] A. N. Gundes and M. G. Kabuli, "Reliable decentralized control," in Proc. American Control Conf., Baltimore, MD, pp. 3359-3363,1992.
[16] R. J. Veillette, J. V. Medanic, and W. R. Perkings, Design of reliable control systems, IEEE Trans. Automat. Contr., vol. 37, pp. 290-304, 1992.
[17] V. Schaft, "$L_2$-gain analysis of nonlinear systems and nonlinear control," IEEE Trans. Automat. Contr., vol. 34, pp. 770-784, 1992.
[18] D. D. Siljak, Reliable control using multiple control systems, Int. J. Contr., vol. 31, no. 2, pp. 303-329,1980.
[19] J. V. Medanic. Design of fault-tolerance controllers using redundant control elements. in Proc. American Control Conf., San Fransisco, California, USA, pp. 3130-3134, 1993.
[20] R. J. Veillette, "Reliable linear-quadratic state feedback control," Automatica, 31, 137-143, 1995.
[21] Y. Zhang, J. Jiang, "Bibliographic review on

reconfigurable fault-tolerant control systems," in Proc. IFAC Safeprocess, Washington, DC, 2003, pp. 265–276.

[22] M. Bodson and J. E. Groszkiewicz, "Multivariable adaptive control algorithms for reconfigurable flight control," IEEE Trans. Contr. Syst. Technol., vol. 5, no. 2, pp. 217–229, Mar. 1997.

[23] Y. Diao and K. M. Passino, "Stable fault tolerant adaptive fuzzy/neural control for a turbine engine," IEEE Trans. Contr. Syst. Technol., vol. 9, no. 3, pp. 494–509, 2001.

[24] J. Jiang, "Design of reconfigurable control systems using eigenstructure assignment," Int. J. Control, vol. 59, pp. 395–410, 1994.

[25] J. D. Boskovic and R. K. Mehra, "Stable multiple model adaptive flight control for accommodation of a large class of control effector failures," in Proc. Amer. Control Conf., pp. 1920–1924, 1999.

[26] Y. Zhang and J. Jiang, "Integrated active fault-tolerant control using IMM approach," IEEE Trans. Aerosp. Electron. Syst., vol. 37, no. 4, pp. 1221–1235, Oct. 2001.

[27] C. Y. Huang and R. F. Stengel, "Restructurable control using proportional-integral- integral implicit model following," J. Guid. Control Dyn., vol. 13, pp. 303–309, 1990.

[28] B. Jiang and F. N. Chowdhury, "Fault estimation and accommodation for linear MIMO discrete-time systems," IEEE Trans. Contr. Syst. Technol., vol. 13, no. 3, pp. 493-499, 2006.

[29] M. Blanke, M. Staroswiecki, and N. E. Wu, "Concepts and methods in fault-tolerant control," in Proc. Amer. Control Conf., Arlington, VA, pp. 2606–2620, 2001.

[30] J. R. Patton, Fault-tolerant control : the 1997 situation. in Proc. IFAC Symp. Fault detection, supervision safety for process, pp. 1033-1055,1997.

[31] D. J. Boskovic, H. S. Yu and K. R. Mehra, A stable scheme for automatic control reconfiguration in the presence of actuator failures, in Proc. Amer. Control Conf., pp: 2455-2459, 1998.

[32] N. E. Wu, Coverage in fault-tolerant control. Automatica, vol. 40, pp. 537-548, 2004.

[33] Y. Zhang, F. Wang and G. Yu. Fault Accommodation of a Class of Nonlinear Systems Using a Learning Approach. ACTA Automatica Sinica. Vol. 30, no. 5, pp: 757-762, 2004.

[34] A. Isodori, Adaptive control of linearizable systems. IEEE Transactions on Automatic Control, 34, (11), 1123-1131, 1989.

[35] S. W. Kim, Fuzzy logic based sliding mode control. Fuzzy Set and Systems, 71, 359-367, 1995.