Direct Adaptive Compensation Control of Mechanical Systems With Unknown Actuator Failures and Dead-Zone Nonlinearities

Xiaohang Su and Zhi Liu[a]

School of Automation, Guangdong University of Technology, Guangzhou, China

Abstract. In this paper, a new tuning function backstepping control scheme is proposed for a class of parametric strict feedback nonlinear systems to accommodate actuator failures/faults and dead-zone constraints, where the failures/faults are uncertain in time, pattern, and values, and the dead-zone parameters are not available. Roughly speaking, such a scheme is developed in two steps below. First, by using an adaptive smooth inverse function to compensate for the dead-zone nonlinearity, we separate the coupling actuator dynamics into two parts, i.e., the dead-zone compensation errors and the nominal failure dynamics. Afterward, we further handle these two parts based on the techniques of robust adaptive approach and parametrization method. With our scheme, the global boundedness of the signals in the closed-loop system are ensured, and the tracking error is steered to zero asymptotically. These results have also been verified through simulation studies.

1 Introduction

In a practical control system, dead-zone characteristic ubiquitously exists in gear friction, hydraulic valves, DC motors and mechanical connection, which usually degrades the performance of the system. In recent years, adaptive compensation control schemes for dead-zone nonlinearity in the presence of parametric uncertainties have been developed. In [1], the dead-zone nonlinearity is regarded as an external bounded disturbance which can be mitigated through robust control design by using a direct decomposition method (DDM). Apart from DDM, the inverse compensation method (ICM) is another effective strategy to eliminate the effects of nonsmooth nonlinearities. Compared to the compensation method DDM, ICM can completely cancel actuator dead-zone by constructing an inverse compensator through parameter identification; see [2]. However, it is usually costly for offline parameter identification. Thus it is of significance to develop an adaptive inverse compensation method (AICM) by using the adaptive technique to estimate unknown dead-zone parameters online; see [3].

Besides the inherent actuator nonlinearities mentioned above, the failures/faults of suddenly getting stuck and losing partial effectiveness may also occur in practical actuation mechanisms. Recently, studies on actuator failures started by handling the linear system failure in [4], and the

[a]Corresponding author : lz@gdut.edu.cn

results were further extended to nonlinear system failure in [5] by the utilizing backstepping technique. With backstepping recursive design, a new prescribed performance bounds (PPB) based controller is proposed in [6] to guarantee the tracking error within the prescribed bounds. Moreover, in the recent work [7], a robust adaptive fault-tolerant control scheme is further proposed for compensating failures in dead-zone actuators. However, such a scheme mainly treats the actuator failures and dead-zone nonlinearity as bounded disturbance-like effects, and thus the perfect asymptotic tracking performance cannot be obtained even for the case of finite number of actuator failures.

Motivated by observations above, in this paper, we study the problem of direct adaptive failure compensation control for a class of uncertain multiple inputs and single output (MISO) nonlinear systems with actuator failures and dead-zone constraints. Such problem is successfully addressed with our newly proposed control methodology with the following contributions.

1) Note that we take actuator failures and dead-zone nonlinearities into account simultaneously in control design, which thus is more general than the existing work [8] that only considered dead-zone effect and [5] that solely focused on actuator failure compensation. Moreover, perfect asymptotic tracking control performance is achieved, irrespective of the existence of such both adversaries.

2) The smooth adaptive inverse is firstly utilized to compensate for dead-zone nonlinearity, such that the compensating errors containing failure parameters between actual function value of dead-zone nonlinearity and its designed dead-zone output, which is then eliminated in the subsequent design.

3) Recently, the authors in [7] proposed a new and novel robust adaptive control scheme, which has been shown to be applicable to compensate for actuator dead-zone and failures/faults. However, such a scheme cannot recover the perfect asymptotic tracking performance when the number of actuator failures become finite. This issue is also successfully addressed with our proposed scheme.

The outline of the paper is organized below. In Section 2, the control problem is formulated, and the related assumptions are given. In Section 3, a desired controller for addressing control problems is constructed and the stability analysis is provided at the end of this section. Finally, simulations on mechanical system with dead-zone and failures/faults are shown in Section 4.

2 System model and problem statement

In this paper, the following uncertain nonlinear system for the adaptive actuator failure compensation problem is considered.

$$\begin{aligned} \dot{x}_i &= x_{i+1} + \varphi_i^T(x_1, x_2, ..., x_i)\vartheta, i = 1, 2, ..., \lambda - 1 \\ \dot{x}_\lambda &= \varphi_0(x,\eta) + \varphi_\lambda^T(x,\eta)\vartheta + \sum_{j=1}^{q} b_j \gamma_j(x,\eta) u_j \\ y &= x_1 \end{aligned} \tag{1}$$

where $x_i \in \Re^i$ are state variables, $y \in \Re$ is the system output, $u_j \in \Re$ for $j = 1, 2, ..., q$ denotes the j th control input to the plant, $\varphi_0 \in \Re, \varphi_i(x) \in \Re^p (i = 1, 2, ..., \lambda)$ and $\gamma_j(x,\eta) \neq 0 (j = 1, 2, ..., q)$ are known smooth nonlinear functions, $\vartheta \in \Re^p$ and $b_j (j = 1, 2, ..., q)$ are unknown parameters and control coefficients, respectively. Denote τ_j as the input of the j th actuator ($j = 1, 2, ..., q$), u_j as the output of the j th actuator ($j = 1, 2, ..., q$). An actuator with its input equals to its output, i.e., $\tau_j = u_j$, namely the failure-free actuators.

As previous analysis, dead-zone is inevitable in most mechanical devices, which can be denoted as

$$v_j = D(\tau_j) = \begin{cases} m_r(\tau_j - d_+) & \tau_j \geq d_+ \\ 0 & d_- < \tau_j < d_+ \\ m_l(\tau_j - d_-) & \tau_j \leq d_- \end{cases} \tag{2}$$

where v_j for $j = 1,2,...,q$ is the j th output of the dead-zone actuator. $d_- \leq 0, d_+ \geq 0$ and $m_r > 0, m_l > 0$ are unknown constants.

Considering the dead-zone actuator with possible unknown failures/faults, the effect of failure nonlinearity can not be simply taken as an external disturbance-like term without considering its structural information, thus the mathematic model for failure is needed below:

$$u_j = \rho_j v_j + v_{sj}, \forall t \geq t_{jF} \tag{3}$$

$$\rho_j v_{sj} = 0, j = 1,2,...q \tag{4}$$

where $\rho_j \in [0,1)$, v_{sj} and t_{jF} are all unknown constants.

The control objectives of this paper are to ensure all the signals of the nonlinear system bounded and the system output y asymptotically tracks the reference signal y_r. To achieve the objectives, the following assumptions are needed.

Assumption 1. The dead-zone parameters satisfy $m_r \geq m_{r0}, m_l \geq m_{l0}$, where m_{r0}, m_{l0} are two small positive constants, as described in [8].

Assumption 2. The reference signal y_r and its first λ th order derivatives $y_r^{(i)}(i = 1,2,...,\lambda)$ are known, bounded and piecewise continuous. $\gamma_i(x,\eta) \neq 0$, and the signs of b_i, i.e., $sgn(b_i)$ are known.

3 Objective controller design for solving the problem

3.1 Dead-zone Inverse Model

In this part, to prevent the system from potential chattering phenomenon in the backstepping recursion, v_j needs to be designed as

$$v_{dj} = -\hat{\theta}_j^T \hat{w}_j, j = 1,2,...,q \tag{5}$$

where $\hat{\theta}_j^T = [m_r, m_r d_+, m_l, m_l d_-]$ is an estimate of θ_j, $\hat{w}_j^T = [-\Phi_1(\tau)\tau_j, \Phi_1(\tau), -\Phi_2(\tau)\tau_j, -\Phi_2(\tau)]$ is an identity matrix. $\Phi_1(v_j) = \dfrac{e^{\frac{v_j}{e_0}}}{e^{\frac{-v_j}{e_0}} + e^{\frac{v_j}{e_0}}}$ and $\Phi_2(v_j) = \dfrac{e^{-\frac{v_j}{e_0}}}{e^{\frac{-v_j}{e_0}} + e^{\frac{v_j}{e_0}}}$ are designed as smooth continuous functions, where $e_0 > 0$ is a user-defined parameter.

Then the corresponding actuator smooth dead-zone inverse model is obtained as:

$$\tau_j = \frac{v_{dj} + m_r d_+}{\hat{m}_r} \Phi_1(v_{dj}) + \frac{v_{dj} + m_l d_-}{\hat{m}_l} \Phi_2(v_{dj}) \tag{6}$$

The compensating errors between v_j and v_{dj} are obtained as

$$v_j - v_{dj} = -\tilde{\theta}_j^T \hat{w}_j + D_{Nj} \tag{7}$$

where $\tilde{\theta}_j = \theta_j - \hat{\theta}_j$, $D_{Nj} = \theta_j^T(\hat{w}_j - w_j)$. D_{Nj} can be guaranteed to be bounded for all $t \geq 0$, see, [8].

3.2 Controller Design

In this subsection, the novel adaptive compensation scheme for actuator failures and dead-zone constraints of nonlinear system is proposed. First of all, the following error variables are introduced as

$$z_1 = x_1 - y_r \tag{8}$$

$$z_i = x_i - \alpha_{i-1} - y_r^{(i-1)}, i = 2,3,...,\lambda \tag{9}$$

Step i ($i = 1,2,...,\lambda - 1$). Based on the tuning function design scheme, the i th stabilizing function α_i and tuning function ς_i are chosen as

$$\alpha_1 = -c_1 z_1 - \varpi_1^T \hat{\vartheta} \tag{10}$$

$$\alpha_i = -z_{i-1} - c_i z_i - \varpi_i^T \hat{\vartheta} + \frac{\partial \alpha_{i-1}}{\partial \hat{\vartheta}} \Gamma \varsigma_i + \sum_{j=1}^{i-1} \Big[\frac{\partial \alpha_{i-1}}{\partial x_j} x_{j+1} + \frac{\partial \alpha_{i-1}}{\partial y_r^{(j-1)}} y_r^{(j)} \Big] + \sum_{j=2}^{i-1} \frac{\partial \alpha_{j-1}}{\partial \hat{\vartheta}} \Gamma \varpi_i z_j, i = 2,...,\lambda - 1 \tag{11}$$

$$\varsigma_i = \varsigma_{i-1} + \varpi_i z_i, \varpi_i = \varphi_i - \sum_{j=1}^{i-1} \frac{\partial \alpha_{i-1}}{\partial x_j} \varphi_j \tag{12}$$

Step λ . From the above definitions, $\dot{z}_\lambda$ is obtained as

$$\dot{z}_\lambda = \varphi_0 + \varphi_\lambda^T \vartheta - \dot{\alpha}_{\lambda-1} - y_r^{(\lambda)} - \sum_{i=1}^{q} b_i \gamma_i(x,\eta) \rho_i \tilde{\theta}_i^T \hat{w}_i + \sum_{i=1}^{q} b_i \gamma_i \rho_i D_{Ni} + \sum_{i=1}^{q} b_i \gamma_i (\rho_i v_{di} + v_{si}) \tag{13}$$

Remark 1: Based on the adaptive inverse compensation method (ACIM), the compensating errors between actual function value and its designed dead-zone output are obtained, as seen in (7). By combining the failure model (3)-(4), we can separate the coupling actuator dynamics into two parts: the dead-zone compensation errors containing failure parameters and the nominal failure dynamics, as shown in (13). These two parts can be compensated by synthesizing robust control approach, parametrization method and direct adaptive approach in following steps.

Supposing one or more of failures suddenly occur in the dead-zone actuators during time interval $[T_{K-1}, T_K)$, where T_{K-1}, T_k for $k = 1,2,...,e,e+1(e \leq q)$ are a finite number of time instants. We define two sets such that $Q_{tot_k} = \{j_{1,1}, j_{1,2},..., j_{1,q_{tot_k}}\}$ and $Q_{par_k} = \{j_{1,1}, j_{1,2},..., j_{1,q_{par_k}}\}$. As previous analysis, the unknown parameters D_{Ni} in (13) can be computed as

$$|b_i D_{Ni}| \leq |b_i| \bar{D}_{Ni} = |b_i| (\tilde{\bar{D}}_{Ni} + \hat{\bar{D}}_{Ni}) \tag{14}$$

Then the Lyapunov function V_λ is chosen as

$$V_\lambda = V_{\lambda-1} + \frac{1}{2} z_\lambda^2 + \sum_{i=1, i \notin Q_{tot_k}}^{q} \frac{\rho_i |b_i|}{2} \tilde{\kappa}^T \Gamma_k^{-1} \tilde{\kappa} + \sum_{i=1}^{q} \frac{\rho_i |b_i|}{2} \tilde{\theta}^T \Gamma_s^{-1} \tilde{\theta} + \sum_{i=1}^{q} \frac{\rho_i |b_i|}{2} \tilde{\bar{D}}_{Ni}^2 \tag{15}$$

where Γ_k and Γ_s are two positive-definite matrices. If b_i, ρ_i and v_{si} for $i = 1, 2, ..., q, h \in Q_{tot_k}$ are known, κ is a desired constant vector such that

$$\sum_{i=1, i \notin Q_{tot_k}}^{q} |b_i| \rho_i \kappa^T \varrho = \alpha_\lambda - \sum_{h \in Q_{tot_k}} b_h \gamma_h v_{sh}, \kappa_1 = \frac{1}{\sum_{i=1, i \notin Q_{tot_k}}^{q} |b_i| \rho_i}, \kappa_{2,h} = \frac{-b_h v_{sh}}{\sum_{i=1, i \notin Q_{tot_k}}^{q} |b_i| \rho_i} \tag{16}$$

where $h \in Q_{tot_k}$ and $h \in \{1, 2, ..., q\} \Rightarrow \kappa_{2,h} = 0$, $\hat{\kappa} = [\hat{\kappa}_1, \hat{\kappa}_2^T]^T$, $\hat{\kappa}_2 = [\hat{\kappa}_{2,1}, \hat{\kappa}_{2,2}, ..., \hat{\kappa}_{2,q}]^T$, $\varrho = [\alpha_\lambda, \gamma_1, ..., \gamma_q]^T$. Then $\dot{V}_\lambda$ can be computed as

$$\begin{aligned}
\dot{V}_\lambda \leq & -\sum_{i=1}^{\lambda-1} c_i z_i^2 + z_\lambda \Big\{ z_{\lambda-1} + \alpha_\lambda + \varphi_0 + \varpi_\lambda^T \hat{\vartheta} - \sum_{i=1}^{\lambda-1} \Big[\frac{\partial \alpha_{\lambda-1}}{\partial x_i} x_{i+1} + \frac{\partial \alpha_{\lambda-1}}{\partial y_r^{(i-1)}} y_r^{(i)} \Big] n - \frac{\partial \alpha_{\lambda-1}}{\partial \hat{\vartheta}} \dot{\hat{\vartheta}} \\
& + \sum_{i=1}^{q} b_i \gamma_i (x, \eta)(\rho_i v_{di} + v_{si}) + \sum_{i=1}^{q} |b_i| \rho_i \gamma_i \hat{\bar{D}}_{Ni} - y_r^{(\lambda)} \Big\} + \tilde{\vartheta}^T (\varsigma_\lambda - \Gamma^{-1} \dot{\hat{\vartheta}}) + \sum_{i=2}^{\lambda-1} z_i \frac{\partial \alpha_{i-1}}{\partial \hat{\vartheta}} (\Gamma \varsigma_{\lambda-1} - \dot{\hat{\vartheta}}) \\
& - \sum_{i=1, i \notin Q_{tot_k}}^{q} |b_i| \rho_i \widetilde{\kappa_i^T} (\varrho z_\lambda + \Gamma_k^{-1} \dot{\hat{\kappa}}) + \sum_{i=1}^{q} |b_i| \rho_i \tilde{\theta}_i^T \Big[|\gamma_i \hat{w}_i z_\lambda| - \Gamma_s^{-1} \dot{\hat{\theta}}_i \Big] + \sum_{i=1}^{q} |b_i| \rho_i \widetilde{\bar{D}_{Ni}} [|\gamma_i z_\lambda| - \dot{\hat{\bar{D}}}_{Ni}]
\end{aligned} \tag{17}$$

To make $\dot{V}_\lambda$ non-positive, the tuning function ς_λ and the stabilizing function α_λ are defined as

$$\varsigma_\lambda = \varsigma_{\lambda-1} + \varpi_\lambda z_\lambda, \ \varpi_\lambda = \varphi_\lambda - \sum_{j=1}^{\lambda-1} \frac{\partial \alpha_{\lambda-1}}{\partial x_j} \varphi_j \tag{18}$$

$$\begin{aligned}
\alpha_\lambda = & -z_{\lambda-1} - c_\lambda z_\lambda - \varphi_0 - \varpi_\lambda^T \hat{\vartheta} + \frac{\partial \alpha_{\lambda-1}}{\partial \hat{\vartheta}} \Gamma \varsigma_\lambda + \sum_{i=2}^{\lambda-1} \frac{\partial \alpha_{i-1}}{\partial \hat{\vartheta}} \Gamma \varpi_\lambda z_i \\
& + \sum_{i=1}^{\lambda-1} \Big(\frac{\partial \alpha_{\lambda-1}}{\partial x_i} x_{i+1} + \frac{\partial \alpha_{\lambda-1}}{\partial y_r^{(i-1)}} y_r^{(i)} \Big) - \sum_{i=1}^{q} |b_i| \rho_i \gamma_i \hat{\bar{D}}_{Ni} + y_r^{(\lambda)}
\end{aligned} \tag{19}$$

The final parameter update laws are chosen as

$$\dot{\hat{\vartheta}} = \Gamma \varsigma_\lambda, \dot{\hat{\kappa}} = -\Gamma_k \varrho z_\lambda, \dot{\hat{\theta}}_i = \Gamma_s |\gamma_i \hat{w}_i z_\lambda|, \dot{\hat{\bar{D}}}_{Ni} = |\gamma_i z_\lambda| \tag{20}$$

The control law v_{di} is finally determined as

$$v_{di} = sgn(b_i)\frac{1}{\gamma_i}\hat{\kappa}^T \varrho, for\ i = 1,2,...,q \tag{21}$$

3.3 Stability Analysis

Theorem: Considering the closed-loop adaptive system consists of the plant (1) with the control law (21) and the parameter update laws (20) in the presence of dead-zone nonlinearity (2) and actuator failures (3)-(4) and under Assumptions 1-2. The boundedness of all the signals are ensured and the tracking error approaches to zero asymptotically, i.e., $\lim_{t\to\infty}[y(t) - y_r(t)] = 0$.

Proof. From **Step i**, we conclude that

$$\dot{z}_1 = z_2 - c_1 z_1 + \varpi_1^T \tilde{\vartheta} \tag{22}$$

$$\dot{z}_i = z_{i+1} - c_i z_i - z_{i-1} + \varpi_i^T \tilde{\vartheta} + \frac{\partial \alpha_{i-1}}{\partial \hat{\vartheta}}(\Gamma \varsigma_i - \dot{\hat{\vartheta}}) + \sum_{j=2}^{i-1} \frac{\partial \alpha_{j-1}}{\partial \hat{\vartheta}} \varpi_i z_j \tag{23}$$

Among $[0, T_1)$, with the control law (20), supposing that b_i is known and $\kappa_{2,h} = 0$ for $k = 1,2,...,q$ is chosen, the derivative of z_λ then satisfies

$$\dot{z}_\lambda = -c_\lambda z_\lambda - z_{\lambda-1} + \varpi_\lambda^T \tilde{\vartheta} - \sum_{i=1}^{q} |b_i| \tilde{\kappa}^T \varrho + \sum_{j=2}^{i-1} \frac{\partial \alpha_{j-1}}{\partial \hat{\vartheta}} \varpi_i z_j - \sum_{i=1}^{q} b_i \gamma_i (x, \eta) \rho_i (\tilde{\theta}_i^T \hat{w}_i - D_{Ni}) \tag{24}$$

Assuming during the time interval $[T_{k-1}, T_k)$ for $k = 2,3,...,r$, the system with the controller (21) and update laws (20) undergoes dead-zone nonlinearity and PLOE type of failure, then we have

$$\dot{V}_{k-1} \le -\sum_{j=1}^{\lambda} c_j z_j^2 \tag{25}$$

where $V_{k-1}(T_k + \Delta(t)) \le V_{k-1}(T_k)$, which shows that $z(t), \tilde{\vartheta}, \tilde{\kappa}, \tilde{\theta}, \tilde{D}_N \in L_\infty$, then the boundedness of $x_1(t),...,x_\lambda(t)$ can be derived successively. Besides, by using Barbalat's lemma and combining with $\dot{z}(t) \in L_2$, the error vector $z(t)$ asymptotic convergence to zero can be proved, i.e., $\lim_{t\to\infty} z(t) = 0$. The proof of the theorem is completed.

4 Simulation studies

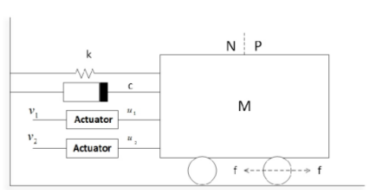

Figure 1. Spring-mass-damper control system with dual actuators.

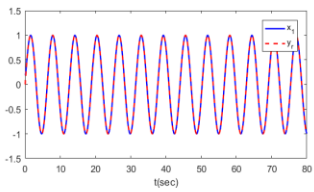

Figure 2

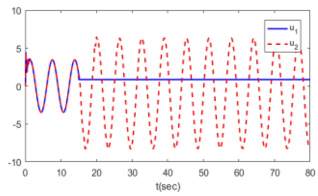

Figure 3

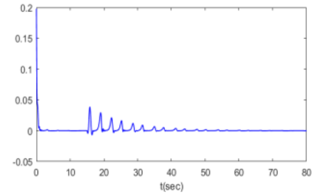

Figure 4

In this example, we apply our approach to the following physical system with dual actuators. For the, visualization, the corresponding physical model is designed in Fig. 1. In addition, the dynamic mathematic model is given as

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -\frac{k}{M}x_1 - \frac{c}{M}x_2 + \frac{1}{M}\sum_{i=1}^{2}u_i \end{aligned} \tag{26}$$

where $y = x_1$ is regarded as the output position of the car whose mass is denoted by $M = 1kg$. $k = 8N/\mathrm{s}$ is the stiffness of the spring, and $c = 2N \cdot m / s$ represents the damping coefficient. For simulation, the initial values are given as $x_1(0) = 0.1m, x_2(0) = 0m/s, u_1(0) = u_2(0) = 0N$ and the reference signal is $y_r = sin(t)$. The dual actuator failure terms are modeled as: at 15th second, the actuator u_1 suffers partial loss of effectiveness (PLOE) as $u_1 = 70\% v_1$. Besides, the maximum static friction of this physical model is chosen as $1N$, which can be regarded as a dead-zone nonlinearity whose parameters are defined as $d_+ = 1N, d_- = -1N, m_r = 1, m_l = 1$.

By choosing the other simulation parameters as $c_1 = 3, c_2 = 2.8$, the results are shown in Fig. 2-Fig. 4. As presented in Fig. 3, the actuator u_1 suffers failure and actuator u_2 works in good condition. By using our proposed control scheme, it can be seen from Fig. 2 that the output signal x_1 tracks the reference signal y_r perfectly. Besides in Fig. 4, the tracking error asymptotically approaches to zero.

5 Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under Grant 61573108, in part by National Natural Science Foundation of China (U1501251), in part by the Natural Science Foundation of Guangdong Province 2016A030313715, in part by the Natural Science Foundation of Guangdong Province through the Science Fund for Distinguished Young Scholars under Grant S20120011437, in part by the Ministry of Education of New Century Excellent Talent under Grant NCET-12-0637.

References

1. Z. Li and C. Y. Su. Neural-adaptive control of single-master-multiple-slaves teleoperation for coordinated multiple mobile manipulators with time-varying communication delays and input uncertainties. IEEE Transactions on Neural Networks and Learning Systems, 24(9):1400-1413, September 2013.

2. D. A. Recker, P. V. Kokotovic, D. Rhode, and J. Winkelman. Adaptive nonlinear control of systems containing a deadzone. Proceedings of the 30th IEEE Conference on Decision and Control, 1991, pages 2111 – 2115, December 1991.
3. G. Tao and P. V. Kokotovic. Adaptive sliding control of plants with unknown dead-zone. IEEE Trans. Autom. Control, 39:59 – 68, January 1994.
4. G. Tao, S. Chen, and S. M. Joshi. An adaptive actuator failure compensation controller using output feedback. IEEE Transactions on Automatic Control, 47(3):506 – 511, March 2002.
5. X. D Tang, G. Tao, and S. M. Joshi. Adaptive actuator failure compensation for nonlinear MIMO systems with an aircraft control application. Automatica, 43(11):1869 – 1883, November 2007.
6. W. Wang and C. Y Wen. Adaptive actuator failure compensation control of uncertain nonlinear systems with guaranteed transient performance. Automatica, 46(12):2082 – 2091, December 2010.
7. Y. X. Li and G. H. Yang. Adaptive fuzzy decentralized control for a class of large-scale nonlinear systems with actuator faults and unknown dead zones. IEEE Transactions on Systems, Man, and Cybernetics: Systems, PP(99):1 – 12, 2016.
8. J. Zhou, C. Wen, and Y. Zhang. Adaptive output control of nonlinear systems with uncertain dead-zone nonlinearity. IEEE Transactions on Automatic Control, 51(3):504 – 511, March 2006.