Static Output Feedback Control of Switched Nonlinear Systems With Actuator Faults

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***Abstract*—This paper is focused on the static output feedback (SOF) control problem for a class of switched nonlinear systems with actuator faults. By means of the Takagi–Sugeno fuzzy model, the switched nonlinear plant is described by a family of switched fuzzy systems. Considering transmission failures may occur between controller and actuator, a reliable SOF controller against actuator faults is designed. Sufficient conditions are developed to guarantee the existence of the reliable SOF controller. Furthermore, an iterative algorithm is designed to determine the controller gains, which avoids the conservatism brought by the traditional singular value decomposition method. To validate the effectiveness of the proposed approach, a numerical example is exploited and simulation results are also presented.**

***Index Terms*—Actuator faults, fuzzy systems, reliable control, switched systems, static output feedback (SOF) control.**

I. Introduction

NONLINEARITIES exist commonly in real world and practical systems are usually nonlinear. Therefore, the investigation of nonlinear systems have been paid considerable attention recently. Since its publication, Takagi–Sugeno (T–S) fuzzy model has been widely recognized as an effective tool to model nonlinear systems [1]. The essential merit of T–S fuzzy models relies on that it is capable of approximating smoothly nonlinear systems to a required precision. Utilizing T–S fuzzy models, the last several decades have witnessed an increasing interest in fuzzy systems, and accordingly, many achievements have been made in this field [2]–[6]. Compared with common fuzzy systems, there also exist a kind of fuzzy systems that are more complex, namely switched fuzzy systems [7]. In spite of their complexities, some important results on switched fuzzy systems have been published in the literature. To mention a few, the problem of model approximation for switched fuzzy systems have been reported in [8], filter design of switched fuzzy systems considering random packet dropouts and time-varying delay has been addressed in [9], asynchronous H_∞ control of switched fuzzy systems has been investigated in [10].

In most cases, the stabilization problem of control systems focuses on state feedback control, which is based on the prerequisite that system states are available. When system states are not available in some practical situations, state observers are often used to estimate system states and the estimated states will be used as alternatives to realize the control purpose, which is also named as dynamic output feedback (DOF) control in the literature. DOF is quite effective to deal with some simple control systems, nevertheless, for complex systems, the inclusion of state observers will make the control problems become more complicated and even difficult to solve. Compared with DOF, static output feedback (SOF) is more reasonable in practice and less expensive to be implemented. Meanwhile, it has been proved in [11] that DOF can be transformed into SOF, which implies that SOF is quite useful in practice. Therefore, it is of no doubt that SOF is popular and has been extensively reported by researchers. For instance, in [12], a system augmentation approach has been proposed to study SOF control of linear Markovian jump systems (MJSs). In [13], a less conservative method on SOF has been presented, where the Lyapunov function does not have to be diagonal. In [14], Cheng *et al.* have solved SOF control of nonhomogeneous MJSs with asynchronous time delays.

On another research front, due to the complexity of modern industrial applications such as networked control systems [15]–[19], flight control systems [20], and communication systems, actuator faults occur inevitably, which will result in instability or poor performance of control systems [21]. To ensure the desired stability and satisfactory performance of control systems, the negative effects caused by actuator faults have to be considered when designing control, thus it is crucial to develop reliable control in the presence of actuator faults. Over the past decades, substantial progress has been made on reliable control and related works can be found in, for example, [22]–[24] and references therein. Despite many efforts have been devoted to reliable control, it is noted that up to now, among all the

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existing works related to reliable control, there are only a few results concerned with reliable control of switched fuzzy systems, especially for reliable SOF control of switched fuzzy systems, which motivates us to carry out this paper.

Summarizing the abovementioned discussions, we concentrate on the stabilization problem for a family of switched fuzzy systems that suffered with actuator faults. Since it is well recognized that SOF is more effective and practical than dynamic output feedback and state feedback to some extent, a reliable SOF controller (RSOFC) is thus designed to realize the control purpose. The stochastic stability of a closed-loop system is analyzed utilizing the basis-dependent Lyapunov function approach and a prescribed dissipative disturbance attenuation constraint is also considered. To determine the controller gains of the designed RSOFC, the singular value decomposition and matrix inequality techniques are considered first. However, within this framework, the output matrices must be constant and full row rank. To avoid this drawback, an iterative algorithm is thus introduced and the desired controller gains are available by solving linear matrix inequalities iteratively. In the end, an example from the literature is used to illustrate the proposed design method and simulation results are presented.

The remainder of this paper is organized as follows. Section II presents the preliminaries and problem to be considered. Section III analyzes the stability and prescribed performance of a closed-loop system. Section IV completes the controller design synthesis and the developed theoretical results are verified by a numerical example in Section V. Finally, Section VI concludes this paper.

Notation: The notations are fairly standard throughout this paper. The notation $X > 0$ $(X \geq Y)$ refers to X is positive definite (positive semidefinite). $l_2[0, +\infty)$ is the space of square-integrable vector functions over $[0, +\infty)$. 0 and I represent the zero matrix and the identity matrix with compatible dimensions, respectively. Also, $E\{x\}$ denotes the expectation of x and $E\{x|y\}$ denotes the expectation of x conditional on y, respectively. $*$ within a matrix stands for the symmetric terms. Finally, unless otherwise stated, it is assumed that all the matrices have suitable dimensions for algebraic operations.

II. Problem Statement

The nonlinear system under consideration is described utilizing the following switched T–S fuzzy model:

IF θ_{1k} is M_{i1}, θ_{2k} is M_{i2}, …, and θ_{pk} is M_{ip}, THEN

$$\begin{cases} x(k+1) = A_{r_k,i}x(k) + B_{r_k,i}u(k) + C_{r_k,i}w(k) \\ z(k) = D_{r_k,i}x(k) + E_{r_k,i}u(k) + F_{r_k,i}w(k) \\ y(k) = G_{r_k,i}x(k),\ i = 1, 2, \ldots, r \end{cases} \tag{1}$$

where $\theta_{jk} \in \{\theta_{1k}, \theta_{2k}, \ldots, \theta_{pk}\}$ is the premise variable, M_{ij} is a given fuzzy set, and r is the total number of IF–THEN rules; $x(k) \in R^n$ is the system state; $u(k) \in R^n$ is the control input; $w(k) \in R^m$ is the exogenous disturbance contained in $l_2[0, \infty)$; $z(k) \in R^v$ denotes the regulated output; and $y(k) \in R^q$ denotes the measurement output.

The variable r_k is the switching signal that used to characterize the switching phenomena. For $r_k \in \{1, 2, 3, \ldots, L\}$, system parameters $A_{r_k i}, B_{r_k i}, C_{r_k i}, D_{r_k i}, E_{r_k i}, F_{r_k i}$, and $G_{r_k i}$ are known and their dimensions are compatible for algebraic operation. Meanwhile, for $l \in \{1, 2, 3, \ldots, L\}$, the variable r_k is state independent and satisfies

$$\Pr\{r_k = l\} = \pi_l, 0 \leq \pi_l \leq 1 \tag{2}$$

and

$$\pi_1 + \pi_2 + \cdots + \pi_L = 1 \tag{3}$$

where π_l stands for the probability of the *l*th subsystem being activated. The work [25] has elaborated on the acquisition of π_l and switching mechanism of r_k, thus more details can be found in [25].

According to related works on T–S fuzzy systems, fuzzy basis functions are crucial for the following analysis and design. Therefore, it is necessary to implement the standard defuzzifier and fuzzifier operations, and then the normalized fuzzy basis functions are given as

$$h_i(\theta_k) = \frac{\varpi_i(\theta_k)}{\sum_{i=1}^{r} \varpi_i(\theta_k)} \tag{4}$$

with $\varpi_i(\theta_k) = \prod_{j=1}^{p} M_{ij}(\theta_{jk})$ and $\theta_k = [\theta_{1k}, \theta_{2k}, \ldots, \theta_{pk}]$ where $M_{ij}(\theta_{jk})$ refers to the grade of membership of θ_{jk} in M_{ij} [26]. In what follows, $h_i(\theta_k)$ is denoted as h_i for simplicity. On the other hand, for any $i = \{1, 2, \ldots r\}$, h_i satisfies

$$h_i \geq 0, \sum_{i=1}^{r} h_i = 1 \tag{5}$$

which will be used in later calculations.

Utilizing aforementioned notations, a compact form of the system (1) is described as

$$\begin{cases} x(k+1) = A_{lh}x(k) + B_{lh}u(k) + C_{lh}w(k) \\ z(k) = D_{lh}x(k) + E_{lh}u(k) + F_{lh}w(k) \\ y(k) = G_{lh}x(k) \end{cases} \tag{6}$$

with

$$\begin{aligned} A_{lh} &= \sum_{i=1}^{r} h_i A_{li}, \quad B_{lh} = \sum_{i=1}^{r} h_i B_{li} \\ C_{lh} &= \sum_{i=1}^{r} h_i C_{li}, \quad D_{lh} = \sum_{i=1}^{r} h_i D_{li} \\ E_{lh} &= \sum_{i=1}^{r} h_i E_{li}, \quad F_{lh} = \sum_{i=1}^{r} h_i F_{li} \\ G_{lh} &= \sum_{i=1}^{r} h_i G_{li} \end{aligned} \tag{7}$$

and $h \triangleq (h_1, h_2, \ldots, h_r) \in \rho$ where ρ are basis functions satisfying (5).

The objective of this paper is to design an SOF controller to stabilize the switched fuzzy system (6). Based on the parallel distributed compensation method, the particular expression of the SOF controller is given as

$$\bar{u}(k) = K_{lh} y(k) \tag{8}$$

with

$$K_{lh} = \sum_{j=1}^{r} h_j K_{lj}. \tag{9}$$

Since when control signals transmitting from controller to actuator, some unexpected faults may occur, the actual control input with actuator faults is modeled as

$$u(k) = \beta \bar{u}(k) \tag{10}$$

where the variable β characterizes faults of the actuator and it is defined as $\beta := \text{diag}\{\beta_1, \beta_2, \ldots, \beta_n\}$.

It should be noted that $\beta_i (i = 1, 2, \ldots, n)$ satisfies

$$0 \leq \underline{\beta}_i \leq \beta_i \leq \overline{\beta}_i \leq 1 \tag{11}$$

in which $\overline{\beta}_i$ and $\underline{\beta}_i$ are the upper and lower bounds of β_i, respectively. Next, defining

$$\begin{aligned}
\overline{\beta} &:= \text{diag}\{\overline{\beta}_1, \overline{\beta}_2, \ldots, \overline{\beta}_n\} \\
\underline{\beta} &:= \text{diag}\{\underline{\beta}_1, \underline{\beta}_2, \ldots, \underline{\beta}_n\} \\
\beta_a &:= \text{diag}\left\{\frac{\overline{\beta}_1 + \underline{\beta}_1}{2}, \frac{\overline{\beta}_2 + \underline{\beta}_2}{2}, \ldots, \frac{\overline{\beta}_n + \underline{\beta}_n}{2}\right\} \\
\beta_b &:= \text{diag}\left\{\frac{\overline{\beta}_1 - \underline{\beta}_1}{2}, \frac{\overline{\beta}_2 - \underline{\beta}_2}{2}, \ldots, \frac{\overline{\beta}_n - \underline{\beta}_n}{2}\right\}.
\end{aligned} \tag{12}$$

Thus, β can be described as

$$\beta = \beta_a + \Delta \tag{13}$$

where

$$\Delta = \text{diag}\{\Delta_1, \Delta_2, \ldots, \Delta_n\}, \quad |\Delta_i| \leq \beta_b.$$

With the abovementioned notations, the closed-loop system of (6) with the controller (10) can be written as follows:

$$\begin{cases} x(k+1) = \bar{A}_{lh} x(k) + C_{lh} w(k) \\ z(k) = \bar{D}_{lh} x(k) + F_{lh} w(k) \end{cases} \tag{14}$$

where

$$\bar{A}_{lh} = A_{lh} + \beta B_{lh} K_{lh} G_{lh}, \;\; \bar{D}_{lh} = D_{lh} + \beta E_{lh} K_{lh} G_{lh}.$$

Before ending this section, it is necessary to present some definitions that will be helpful in the subsequent sections.

Definition 1: For any initial condition and under the case of $w(k) \equiv 0$, the closed-loop system (14) is called stochastically stable provided the following condition can be satisfied:

$$E\left\{\sum_{k=0}^{\infty} \|\varsigma(k)\|^2 | \varsigma(0)\right\} < \infty. \tag{15}$$

Definition 2 [27]: Consider the following performance function

$$J(z(k), w(k), T) = \sum_{k=0}^{T} E\{\mathcal{G}(z(k), w(k))\}$$

with

$$\mathcal{G}(z(k), w(k)) = z^T(k)\mathcal{Q}z(k) + 2z^T(k)\mathcal{S}w(k) + w^T(k)\mathcal{R}w(k)$$

where matrices $\mathcal{Q}$, $\mathcal{R}$, and $\mathcal{S}$ are given and satisfying $\mathcal{Q}{=}\mathcal{Q}^T{<}0$, $\mathcal{R} = \mathcal{R}^T$. For any integer $T > 0$, if $0 \leq J(z(k), w(k), T)$ holds under zero initial condition, then the closed-loop system (14) is said to be dissipative. Moreover, if

$$\tau \sum_{k=0}^{T} E\{w^T(k)w(k)\} < J(z(k), w(k), T) \tag{16}$$

holds for a scalar $\tau > 0$, then the closed-loop system (14) is strictly dissipative with the given performance index τ [28].

Now, the problem to be solved in this paper is formulated as follows. For a given index τ and the switched fuzzy system (6), design an RSOFC (10) to ensure the closed-loop system (14) is strictly ($\mathcal{Q}$, $\mathcal{S}$, $\mathcal{R}$) dissipative and stochastically stable. In particular, verifiable conditions should be derived to ensure the existence of the controller (10). Meanwhile, the designed controller (10) should guarantee conditions (15) and (16) are satisfied simultaneously for the closed-loop system (14).

Remark 1: It should be underscored that the actuator faults model used in this paper is fairly general. When choosing appropriate values for parameters $\underline{\beta}_i$ and $\overline{\beta}_i$, the actuator faults model can be reduced to some special cases. In particular, taking $\underline{\beta}_i{=}\overline{\beta}_i = 1$, it corresponds to the fully operating case and no actuator faults occur; taking $\underline{\beta}_i{=}\overline{\beta}_i = 0$, it corresponds to the outage case and no control signals can be transmitted to the actuator; taking $0 < \underline{\beta}_i \leq \overline{\beta}_i < 1$, it corresponds to the case that the actuator faults occur with varying degrees.

Remark 2: The essential of dissipative systems is that the amount of energy they stored cannot exceed that supplied by the external environment or systems connected with them. Due to the nice property of dissipative systems, they have been extensively investigated in the control field. From another perspective, dissipative systems are actually a generalization of passive systems [29]–[31] and they exist commonly in real world applications, such as mechanical systems and electrical systems.

III. Reliability and Dissipativity Analysis

Based on the fuzzy basis-dependent technique, the stochastic stability and prescribed dissipative performance of the closed-loop system (14) is investigated in this section. Moreover, it is proved that the designed controller (10) is reliable to deal with actuator faults. Before presenting the main result, the following Lemma, which will be used in the subsequent proof, is introduced first.

Lemma 1 [32]: For real matrices $\Xi = \Xi^T$, U, and H that have compatible dimensions, the inequality

$$\Xi + H\Lambda U + U^T\Lambda^T H^T < 0 \tag{17}$$

holds for any matrix Λ satisfying $\Lambda^T\Lambda \le I$ iff there exist some $\varepsilon > 0$ such that

$$\Xi + \varepsilon^{-1}HH^T + \varepsilon U^T U < 0 \tag{18}$$

or equivalently

$$\begin{bmatrix} \Xi & H & \varepsilon U^T \\ H^T & -\varepsilon I & 0 \\ \varepsilon U & 0 & -\varepsilon I \end{bmatrix} < 0.$$

Then, we are in a position to present the reliability and dissipativity analysis, which is the basis for the subsequent controller design. The main result of this part is contained in the following theorem.

Theorem 1: Consider the switched fuzzy system (6) with given controller gains and a predefined scalar $\tau > 0$, if we can find matrices $N_{li} > 0$, $P_i > 0$, $K_{lj} > 0$ such that

$$\sum_{l=1}^{L} \pi_l N_{li} < P_i \tag{19}$$

$$\Theta_{tlij} + \Theta_{tlji} < 0, \quad (i \le j) \tag{20}$$

where

$$\Theta_{tlij} = \begin{bmatrix} -P_t^{-1} & 0 & \breve{A}_{lij} & C_{li} & 0 & \varepsilon\beta_b B_{li} \\ * & \mathcal{Q}^{-1} & \breve{D}_{lij} & F_{li} & 0 & \varepsilon\beta_b E_{li} \\ * & * & -N_{li} & -D_{li}^T\mathcal{S} & \theta_{35} & 0 \\ * & * & 0 & -\theta_{44} & 0 & 0 \\ * & * & * & * & -\varepsilon I & 0 \\ * & * & * & * & * & -\varepsilon I \end{bmatrix}$$

$$\breve{A}_{lij} = A_{li} + \beta_a B_{li} K_{lj} G_{li}, \ \breve{D}_{lij} = D_{li} + \beta_a E_{li} K_{lj} G_{li}$$

$$\theta_{35} = G_{li}^T K_{lj}^T, \ \theta_{44} = \mathcal{R} + 2F_{li}^T\mathcal{S} - \tau I$$

then the stochastic stability and the dissipative performance τ of the closed-loop system (14) can be ensured.

Proof: Based on the fuzzy basis functions defined in Section II, it follows from (20) that

$$\begin{aligned} &\sum_{i=1}^{r}\sum_{j=1}^{r}\sum_{t=1}^{r} h_i h_j h_t \Theta_{tlij} \\ &= \sum_{t=1}^{r} h_t \left\{ \sum_{i=1}^{r} h_i^2 \Theta_{tlii} + \sum_{i=1}^{r-1}\sum_{j=i+1}^{r} h_i h_j (\Theta_{tlij} + \Theta_{tlji}) \right\} \\ &= \begin{bmatrix} -P_{h^+}^{-1} & 0 & \breve{A}'_{lh} & C_{lh} & 0 & \varepsilon\beta_b B_{lh} \\ * & \mathcal{Q}^{-1} & \breve{D}'_{lh} & F_{lh} & 0 & \varepsilon\beta_b E_{lh} \\ * & * & -N_{lh} & -D_{lh}^T\mathcal{S} & \theta'_{35} & 0 \\ * & * & 0 & -\theta'_{44} & 0 & 0 \\ * & * & * & * & -\varepsilon I & 0 \\ * & * & * & * & * & -\varepsilon I \end{bmatrix} \\ &< 0 \end{aligned}$$

with

$$\begin{aligned} \breve{A}'_{lh} &= A_{lh} + \beta_a B_{lh} K_{lh} G_{lh} \\ \breve{D}'_{lh} &= D_{lh} + \beta_a E_{lh} K_{lh} G_{lh} \\ \theta'_{35} &= G_{lh}^T K_{lh}^T \\ \theta'_{44} &= \mathcal{R} + 2F_{lh}^T\mathcal{S} - \tau I. \end{aligned}$$

It is noted that the condition (20) shows $\Theta_{tlii} < 0$ $(i = j)$ and $\Theta_{tlij} + \Theta_{tlji} < 0$ $(i \le j)$, which together with basic fuzzy principles result in the abovestated inequality [3]. On the other hand, a combination of the Schur complement and the abovestated inequality yields

$$\begin{bmatrix} -P_{h^+}^{-1} & 0 & \breve{A}'_{lh} & C_{lh} \\ * & \mathcal{Q}^{-1} & \breve{D}'_{lh} & F_{lh} \\ * & * & -N_{lh} & -D_{lh}^T\mathcal{S} \\ * & * & 0 & -\theta_{44} \end{bmatrix} + \varepsilon \begin{bmatrix} \beta_b B_{lh} \\ \beta_b E_{lh} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} \beta_b B_{lh} \\ \beta_b E_{lh} \\ 0 \\ 0 \end{bmatrix}^T + \varepsilon^{-1} \begin{bmatrix} 0 \\ 0 \\ G_{lh}^T K_{lh}^T \\ 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ G_{lh}^T K_{lh}^T \\ 0 \end{bmatrix}^T < 0$$

and by noting the inequality in (13), one has $\Delta^T\Delta < \beta_b^T\beta_b$, thus it is obvious that

$$\begin{bmatrix} -P_{h^+}^{-1} & 0 & \breve{A}'_{lh} & C_{lh} \\ * & \mathcal{Q}^{-1} & \breve{D}'_{lh} & F_{lh} \\ * & * & -N_{lh} & -D_{lh}^T\mathcal{S} \\ * & * & 0 & -\theta'_{44} \end{bmatrix} + \varepsilon \begin{bmatrix} \Delta B_{lh} \\ \Delta E_{lh} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} \Delta B_{lh} \\ \Delta E_{lh} \\ 0 \\ 0 \end{bmatrix}^T + \varepsilon^{-1} \begin{bmatrix} 0 \\ 0 \\ G_{lh}^T K_{lh}^T \\ 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ G_{lh}^T K_{lh}^T \\ 0 \end{bmatrix}^T < 0.$$

According to Lemma 1, the abovestated inequality readily becomes

$$\begin{bmatrix} -P_{h^+}^{-1} & 0 & \bar{A}_{lh} & C_{lh} \\ * & \mathcal{Q}^{-1} & \bar{D}_{lh} & F_{lh} \\ * & * & -N_{lh} & -D_{lh}^T\mathcal{S} \\ * & * & 0 & -\theta'_{44} \end{bmatrix} < 0. \tag{21}$$

Then, consider the following Lyapunov function candidate:

$$V(k) = x^T(k) P_h x(k), \quad P_h = \sum_{i=1}^{r} h_i P_i. \tag{22}$$

Along the trajectories of closed-loop system (14), the difference of $V(k)$ is calculated as

$$\begin{aligned} E\{\Delta V(k)\} &= E\{V_{k+1}|x(k)\} - V(k) \\ &= E\{x^T(k+1)P_{h^+}x(k+1)\} - x^T(k)P_h x(k) \\ &= \begin{bmatrix} x(k) \\ w(k) \end{bmatrix}^T \sum_{l=1}^{L} W_{1lh} \begin{bmatrix} x(k) \\ w(k) \end{bmatrix} - x^T(k)P_h x(k) \end{aligned}$$

where

$$W_{1lh} = \begin{bmatrix} \bar{A}_{lh}^T \\ C_{lh}^T \end{bmatrix} P_{h^+} \begin{bmatrix} \bar{A}_{lh}^T \\ C_{lh}^T \end{bmatrix}^T.$$

Under the case of $w(k) = 0$, the difference of $V(k)$ becomes

$$\begin{aligned} E\{\Delta V(k)\} &= x^T(k) \left(\sum_{l=1}^{L} \pi_l \bar{A}_{lh}^T P_{h^+} \bar{A}_{lh} - P_h \right) x(k) \\ &\leq x^T(k) \sum_{l=1}^{L} \pi_l \left(\bar{A}_{lh}^T P_{h^+} \bar{A}_{lh} - N_{lh} \right) x(k). \end{aligned}$$

Applying the Schur complement to (20), it follows that

$$\bar{A}_{lh}^T P_{h^+} \bar{A}_{lh} - N_{lh} < 0$$

i.e., $E\{\Delta V(k)\} < 0$, which meets the requirement of Definition 1 and thus the stochastic stability of the closed-loop system (14) is verified.

Next, to achieve the dissipative performance of the closed-loop system (14), considering the following performance function:

$$\begin{aligned} & E\{\Delta V(k) + \tau w^T(k)w(k) - \mathcal{G}(z(k), w(k)\} \\ &= E\{\Delta V(k) - z^T(k)\mathcal{Q}z(k) - 2z^T(k)\mathcal{S}w(k) + w^T(k) \\ &\quad \times (\tau I - \mathcal{R})w(k)\} \\ &= \begin{bmatrix} x(k) \\ w(k) \end{bmatrix}^T \sum_{l=1}^{L} \pi_l \left(W_{2lh} - \begin{bmatrix} P_h & \bar{D}_{lh}^T \mathcal{S} \\ * & \theta'_{44} \end{bmatrix} \right) \begin{bmatrix} x(k) \\ w(k) \end{bmatrix} \\ &\leq \begin{bmatrix} x(k) \\ w(k) \end{bmatrix}^T \sum_{l=1}^{L} \pi_l \left(W_{2lh} - \begin{bmatrix} N_{lh} & \bar{D}_{lh}^T \mathcal{S} \\ * & \theta'_{44} \end{bmatrix} \right) \begin{bmatrix} x(k) \\ w(k) \end{bmatrix} \end{aligned}$$

where

$$W_{2lh} = \begin{bmatrix} \bar{A}_{lh}^T \\ C_{lh}^T \end{bmatrix} P_{h^+} \begin{bmatrix} \bar{A}_{lh}^T \\ C_{lh}^T \end{bmatrix}^T + \begin{bmatrix} \bar{D}_{lh}^T \\ F_{lh}^T \end{bmatrix} \mathcal{Q} \begin{bmatrix} \bar{D}_{lh}^T \\ F_{lh}^T \end{bmatrix}^T$$

and the inequality is induced by $\sum_{l=1}^{L} \pi_l N_{lh} < P_h$ and (3).

Combining the Schur complement with (21) implies that

$$W_{2lh} - \begin{bmatrix} N_{lh} & \bar{D}_{lh}^T \mathcal{S} \\ * & \theta'_{44} \end{bmatrix} < 0$$

which clearly means that

$$E\{\Delta V(k) + \tau w^T(k)w(k) - \mathcal{G}(e(k), w(k))\} < 0$$

for $k = 0, 1, 2, \ldots, T$. Summing up the left and right sides of the abovestated inequality simultaneously, it is obvious that

$$\sum_{k=0}^{T} E\{\Delta V(k) + \tau w^T(k)w(k) - \mathcal{G}(e(k), w(k))\} < 0.$$

Considering zero-initial conditions and $V(k) \geq 0$, one readily obtains

$$\sum_{k=0}^{T} E\{\tau w^T(k)w(k) - \mathcal{G}(e(k), w(k))\} < 0$$

from which it is concluded that the inequality (16) holds. Therefore, the predefined dissipitivity of the closed-loop system (14) is ensured and the proof is completed. ■

Remark 3: It should be clarified that for the switched fuzzy systems (6), two subsystems cannot be activated simultaneously, that is

$$\begin{cases} \Pr\{r_k = l_1, r_k = l_2\} = \pi_{l_1}, & l_1 = l_2 \\ \Pr\{r_k = l_1, r_k = l_2\} = 0, & l_1 \neq l_2 \end{cases} \tag{23}$$

for any $l_1, l_2 \in \{1, 2, 3, \ldots, L\}$ [7]. Accordingly, it can be checked that

$$E\{\pi_{l_1}\pi_{l_2}\} = \begin{cases} \pi_{l_1}, \ l_1 = l_2 \\ 0, \ l_1 \neq l_2. \end{cases} \tag{24}$$

IV. Controller Design

In this section, the purpose is to solve the controller gains in (10). It may be found that condition (20) is not strictly linear, thus one has to linearize condition (20) such that it can be handled by mathematical softwares. Toward this end, two different linearization procedures are presented. The first is based on singular value decomposition and matrix inequality techniques, whereas the other is based on an iterative algorithm.

It should be underscored that to use the first linearization procedure, a constraint on output matrix G_{li} has to be imposed, namely G_{li} must be invariant and full row rank ($G_{li} = G$). In particular, using the standard singular value decomposition, G is decomposed as

$$G = G_1 \begin{bmatrix} G_2 & 0 \end{bmatrix} G_3^T \tag{25}$$

with

$$G_1 G_1^T = I, \ \ G_3 G_3^T = I. \tag{26}$$

On the other hand, it needs to construct a slack matrix Y such that controller gains can be solved

$$Y = G_3 \begin{bmatrix} G_2^{-1} G_1^T Y_1 & 0 \\ Y_2 & Y_3 \end{bmatrix} G_3^T \tag{27}$$

where Y_1, Y_2, and Y_3 are free matrices. In the following theorem, we are ready to solve the controller gains using the first linearization procedure.

Theorem 2: Given the switched fuzzy system (6) and a predefined scalar $\tau > 0$, a feasible controller (10) exists such that the closed-loop system (14) is stochastically stable with the prescribed dissipative performance τ, if matrices $\hat{N}_{li} > 0$, $\bar{P}_i > 0$,

$\hat{K}_{lj} > 0$, and a scalar $\varepsilon > 0$ can be found such that

$$\sum_{l=1}^{L} \pi_l \hat{N}_{li} < \hat{P}_i \quad (28)$$

$$\hat{\Theta}_{tlij} + \hat{\Theta}_{tlji} < 0, \ \ (i \le j) \quad (29)$$

where

$$\hat{\Theta}_{tlij} = \begin{bmatrix} \mathcal{P}_t & 0 & \hat{A}_{lij} & C_{li} & 0 & \varepsilon\beta_b B_{li} \\ * & \mathcal{Q}^{-1} & \hat{D}_{lij} & F_{li} & 0 & \varepsilon\beta_b E_{li} \\ * & * & -\hat{N}_{li} & -\hat{\theta}_{34} & \hat{\theta}_{35} & 0 \\ * & * & 0 & -\theta_{44} & 0 & 0 \\ * & * & * & * & -\varepsilon I & 0 \\ * & * & * & * & * & -\varepsilon I \end{bmatrix}$$

and

$$\hat{N}_{li} = Y^T N_{li} Y$$
$$\hat{P}_t = Y^T P_t Y$$
$$\mathcal{P}_t = \hat{P}_t - Y^T - Y$$
$$\hat{A}_{lij} = A_{li} Y + \beta_a B_{li} \hat{K}_{li} G_3^T$$
$$\hat{D}_{lij} = D_{li} Y + \beta_a E_{li} \hat{K}_{li} G_3^T$$
$$\hat{K}_{lj} = \begin{bmatrix} \check{K}_{lj} & 0 \end{bmatrix}$$
$$\hat{\theta}_{34} = Y^T D_{li}^T \mathcal{S}$$
$$\hat{\theta}_{35} = G_3 \hat{K}_{li}^T.$$

Furthermore, the controller gains can be inferred as

$$K_{lj} = \check{K}_{lj} Y_1^{-1}. \quad (30)$$

Proof: Since $\hat{N}_{li} = Y^T N_{li} Y$ and $\hat{P}_t = Y^T P_t Y$, it is obvious that by pre-multiplying Y^{-T} and post-multiplying Y^T to the inequality (28), we can readily get the condition (19).

Recalling

$$Y^T P_t Y - Y - Y^T \ge -P_t^{-1} \quad (31)$$

which means $\mathcal{P}_t \ge -P_t^{-1}$. Combine this with condition (29), we have

$$\bar{\Theta}_{tlij} + \bar{\Theta}_{tlji} < 0, \ \ (i \le j) \quad (32)$$

where

$$\bar{\Theta}_{tlij} = \begin{bmatrix} -P_t^{-1} & 0 & \hat{A}_{lij} & C_{li} & 0 & \varepsilon\beta_b B_{li} \\ * & \mathcal{Q}^{-1} & \hat{D}_{lij} & F_{li} & 0 & \varepsilon\beta_b E_{li} \\ * & * & -\hat{N}_{li} & -\hat{\theta}_{34} & \hat{\theta}_{35} & 0 \\ * & * & 0 & -\theta_{44} & 0 & 0 \\ * & * & * & * & -\varepsilon I & 0 \\ * & * & * & * & * & -\varepsilon I \end{bmatrix}.$$

Noting that based on (25)–(27) and (30), the following is deduced:

$$\begin{aligned} \hat{K}_{lj} G_3^T &= \begin{bmatrix} \check{K}_{lj} & 0 \end{bmatrix} G_3^T \\ &= K_{lj} \begin{bmatrix} Y_1 & 0 \end{bmatrix} G_3^T \\ &= K_{lj} G_1 \begin{bmatrix} G_2 & 0 \end{bmatrix} G_3^T G_3 \begin{bmatrix} G_2^{-1} G_1^T Y_1 & 0 \\ Y_2 & Y_3 \end{bmatrix} G_3^T \\ &= K_{lj} G Y. \end{aligned}$$

Now it is clear that replacing $\hat{K}_{lj} G_3^T$ with $K_{li} G Y$ in the inequality (29), then performing a congruence transformation to (29) by $\mathrm{diag}\{Y^{-T}, I, Y^{-T}, I, I, I\}$, the inequality (20) follows immediately. Therefore, the conditions of Theorem 2 can be derived from that of Theorem 1, which completes the proof. ■

Noting that in Theorem 1, although the resulting conditions (28) and (29) are strictly linear and the controller gains are given explicitly, some constraints have to be met for the output matrix. In particular, G_{li} must be invariant and full row rank, which inevitably brings some conservatism to the controller design scheme. To circumvent this problem, we borrow the idea of Ghaoui *et al.*[33], where a new variable is used to replace the inverse matrix of P_t, and then utilize an iterative algorithm to guarantee the new variable matches with the inverse matrix of P_t. As a result, the conditions given in Theorem 1 can be linearized and corresponding controller gains can be solved.

The iterative algorithm proposed in [33] is referred as cone complementarity linearization (CCL) algorithm, with which it is possible to convert the nonconvex problem in Theorem 1 into a sequential optimization problem. Specifically, the essential idea of CCL is to introduce a new inequality

$$\begin{bmatrix} P_t & I \\ I & Q_t \end{bmatrix} \ge 0. \quad (33)$$

If (33) is feasible for positive definite matrices P_t and Q_t, then $\mathrm{tr}(P_t Q_t) \ge n$ holds. Moreover, it can be observed that $\mathrm{tr}(P_t Q_t) = n \Leftrightarrow P_t Q_t = I$, that is, Q_t can be used to replace the inverse of P_t if $\mathrm{tr}(P_t Q_t) = n$. According to this, we replace the term P_t^{-1} in (20) with Q_t, then the optimization problem need to be solved is formulated as follows.

Problem RSOFC:

Minimize $\mathrm{tr}(P_t Q_t)$

subject to (19), (20), and

$$\begin{bmatrix} -P_t & -I \\ -I & -Q_t \end{bmatrix} \le 0. \quad (34)$$

Based on the conclusion of the work in [33], when the solution of min $\mathrm{tr}(P_t Q_t) = rn$, the RSOFC optimization problem is solvable and the conditions of Theorem 1 are satisfied. Now, by modifying [33, Algorithm 1], the specific steps of the proposed algorithm are carried out in the following.

Algorithm RSOFC

Step 1: Given a performance index τ and a maximum permission iterative number $Z > 0$.

Step 2: Find feasible matrices P_t^0, Q_t^0, N_{li}^0, and K_{lj}^0 and scalar ε^0 that satisfy inequalities (19), (20), and (34). Set iteration number $\rho = 0$.

Step 3: Check whether $\rho < Z$. If $\rho < Z$, continue. Otherwise, exit.

Step 4: Solve the following convex problem:
Minimize trace $\sum_{t=1}^{r}(P_t Q_t^\rho + P_t^\rho Q_t)$
subject to (19), (20), and (34).

Step 5: Substitute obtained matrices P_t, Q_t, N_{li}, K_{lj}, and ε into (19) and (20). If (19) and (20) can be satisfied and the following inequality:

$$\left|\sum_{t=1}^{r}(P_t Q_t^\rho + P_t^\rho Q_t) - 2rn\right| < \sigma \tag{35}$$

holds for a sufficiently small scalar $\sigma > 0$, then output the resulting gains K_{lj} and exit.

Step 6: If any one of the inequalities (19), (20), or (35) in Step 4 is not satisfied, set $\rho = \rho + 1$, $P_t^{\rho+1} = P_t^\rho$, $Q_t^{\rho+1} = Q_t^\rho$, $N_{li}^{\rho+1} = N_{li}^\rho$, $K_{lj}^{\rho+1} = K_{lj}^\rho$, $\varepsilon^{\rho+1} = \varepsilon^\rho$, and go to Step 3.

Remark 4: The singular value decomposition and matrix inequality techniques are utilized in Theorem 2 to solve the controller gains, as a result, the conditions given in Theorem 2 are easy to verify and tractable with MATLAB. Despite that the design conservatism of Theorem 2 is also obvious, that is, the slack matrix Y must be endowed with a special structure and the bounding inequality (31) is needed. In the iterative algorithm we provided previously, the derived conditions are equivalent to that of Theorem 1, thus no conservatism is introduced theoretically. Nevertheless, when the numbers of switching models or fuzzy rules increase, the computation burden of the RSOFC algorithm will become far more larger than that of Theorem 2, which is the main drawback of the RSOFC algorithm. In [34], the advantages and disadvantages of both procedures have been discussed in detail.

V. Numerical Example

In this section, a numerical example borrowed from [10] is used to test the effectiveness and performance of the RSOFC (10).

Consider the switched fuzzy system (1) with following parameters:

$$A_{11} = \begin{bmatrix} -0.45 & 0.2 \\ 0.8 & -0.52 \end{bmatrix},\ A_{12} = \begin{bmatrix} 0.85 & -0.6 \\ 0.3 & -1.36 \end{bmatrix}$$
$$B_{11} = \begin{bmatrix} 0.1 \\ -0.8 \end{bmatrix},\ B_{12} = \begin{bmatrix} -0.2 \\ -0.6 \end{bmatrix}$$
$$C_{11} = \begin{bmatrix} 0.7 \\ 1.1 \end{bmatrix}, C_{12} = \begin{bmatrix} -0.5 \\ 1.2 \end{bmatrix}$$
$$D_{11} = \begin{bmatrix} 0.2 & 0.3 \end{bmatrix},\ D_{12} = \begin{bmatrix} 0.9 & -0.35 \end{bmatrix}$$
$$E_{11} = -0.3,\ E_{12} = 0.4,\ F_{11} = 0.5,\ F_{12} = -1$$
$$A_{21} = \begin{bmatrix} 0.6 & -0.1 \\ 1.6 & -0.31 \end{bmatrix},\ A_{22} = \begin{bmatrix} 1.31 & 0.1 \\ 0.6 & 0.5 \end{bmatrix}$$
$$B_{21} = \begin{bmatrix} 0.6 \\ 0.52 \end{bmatrix},\ B_{22} = \begin{bmatrix} 0.45 \\ -0.3 \end{bmatrix}$$
$$C_{21} = \begin{bmatrix} 0.5 \\ 2.1 \end{bmatrix}, C_{22} = \begin{bmatrix} 1.16 \\ 1.3 \end{bmatrix}$$
$$D_{21} = \begin{bmatrix} -0.8 & 0.6 \end{bmatrix},\ D_{22} = \begin{bmatrix} 0.5 & 0.33 \end{bmatrix}$$
$$E_{21} = 0.68,\ E_{22} = -0.4,\ F_{21} = 0.35,\ F_{22} = 0.4$$
$$A_{31} = \begin{bmatrix} 0.4 & -0.2 \\ -0.6 & 0.45 \end{bmatrix},\ A_{32} = \begin{bmatrix} -0.9 & -0.17 \\ 0.1 & 0.3 \end{bmatrix}$$
$$B_{31} = \begin{bmatrix} -0.8 \\ 0.3 \end{bmatrix},\ B_{32} = \begin{bmatrix} 0.1 \\ 0.2 \end{bmatrix}$$
$$C_{31} = \begin{bmatrix} -0.9 \\ -0.6 \end{bmatrix}, C_{32} = \begin{bmatrix} 1.2 \\ 0.5 \end{bmatrix}$$
$$D_{31} = \begin{bmatrix} -0.5 & 0.25 \end{bmatrix},\ D_{32} = \begin{bmatrix} -0.2 & 0.4 \end{bmatrix}$$
$$E_{31} = 0.2,\ E_{32} = -0.8,\ F_{31} = -0.5,\ F_{32} = -0.9.$$

The corresponding fuzzy membership functions are given as

$$h_1 = \frac{1 - x_i(k)}{2},\ h_2 = \frac{x_i(k) + 1}{2},\ i = 1, 2$$

whereas the exogenous disturbance $w(k)$ is assumed to be

$$w(k) = 2\text{sin}(k)e^{-0.2k}.$$

Besides, we choose dissipative parameters as $\mathcal{Q} = -0.09$, $\mathcal{S} = -2, \mathcal{R} = 20$ and switching probabilities as $\pi_1 = 0.2, \pi_2 = 0.3$, $\pi_3 = 0.5$ (see Fig. 1).

Then, the essential purpose to be achieved is that under given fuzzy rules and switching signals, design an RSOFC (10) that satisfies conditions (15) and (16). To this end, setting dissipative performance index $\tau = 3.5$ and maximum permission iterative number $Z = 100$ and then following the steps of the proposed RSOFC algorithm in Section IV, we readily obtain the iterative number is 11 and the feasible controller gains are

$$K_{1,1} = 1.222, \quad K_{1,2} = -0.529$$
$$K_{2,1} = -1.717, \quad K_{2,2} = -3.816$$
$$K_{3,1} = 1.409, \quad K_{3,2} = 2.220.$$

In Fig. 2, the actuator faults model is presented clearly, which shows the variable β used to characterize faults of the actuator varies between 0.6 and 0.8. It can be easily checked that the open-loop system is unstable, then in Fig. 3, closed-loop system state responses are presented. The curves of Fig. 3 indicate that the designed RSOFC is effective to stabilize the open-loop system in the presence of actuator faults, and thus the reliability of the designed RSOFC is demonstrated. Fig. 4 depicts the curves of control input $\bar{u}(k)$ and actual input $u(k)$, which are different due to the existence of actuator faults. Finally, to check

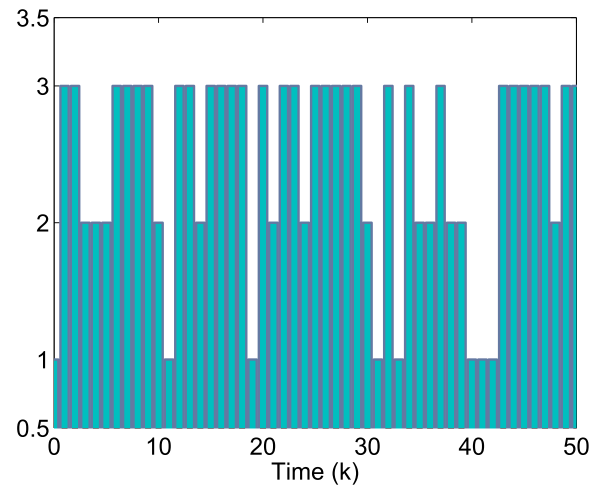

Fig. 1. Switching signals.

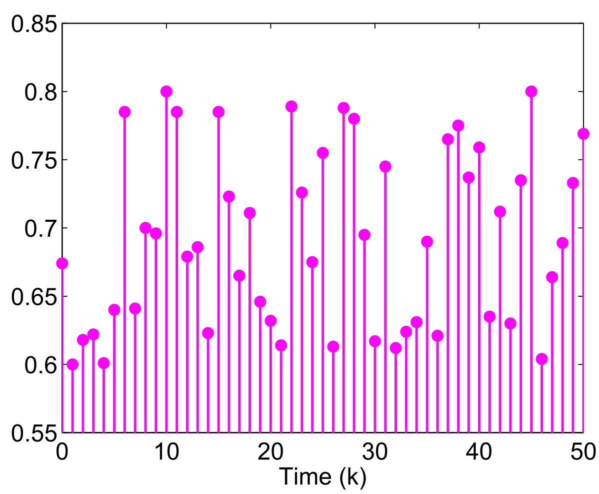

Fig. 2. Actuator faults model.

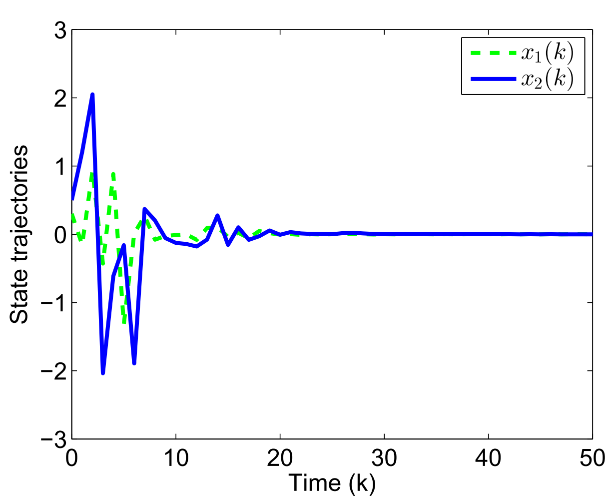

Fig. 3. Closed-loop system state responses.

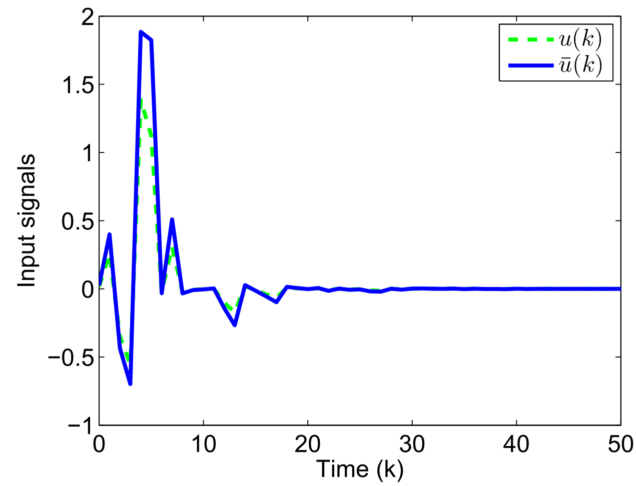

Fig. 4. Input $\bar{u}(k)$ and actual input $u(k)$.

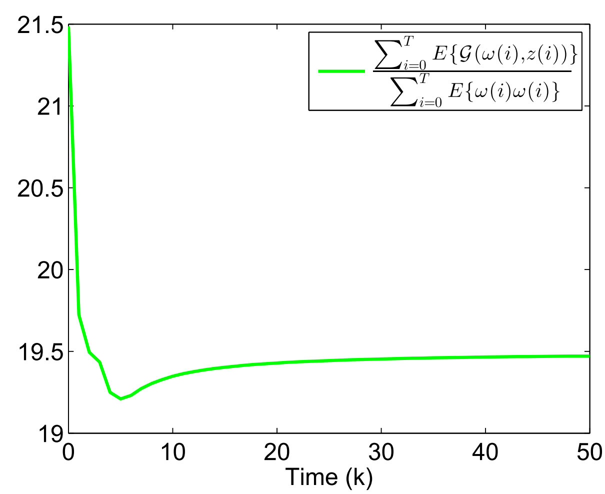

Fig. 5. Dissipative performance of closed-loop system.

TABLE I
ITERATIVE NUMBERS UNDER DIFFERENT τ AND β

The ranges of β	[0.5, 0.7]	[0.6, 0.8]	[0.7, 0.9]
dissipative performance ($\tau = 4.0$)	infeasible	16	9
dissipative performance ($\tau = 3.5$)	27	11	7
dissipative performance ($\tau = 3.0$)	17	9	6
dissipative performance ($\tau = 2.5$)	12	7	5

the dissipative performance of the closed-loop system, Fig. 5 is carried out. It is observed from Fig. 5 that the minimum value of $\frac{\sum_{i=0}^{T} E\{\mathcal{G}(\omega(i),z(i))\}}{\sum_{i=0}^{T} E\{\omega(i)\omega(i)\}}$ is greater than 19, whereas the prescribed value is 3.5, hence the designed RSOFC is capable of ensuring the dissipative performance of the closed-loop system.

To quantitatively validate the dissipative performance of closed-loop system (14) with controller (10) designed by the proposed algorithm RSOFC, Table I is presented, which shows the iterative numbers under different dissipative performance indexes τ and ranges of β. It is observed from Table I that bigger dissipative performance indexes and ranges of β result in bigger iterative numbers, which is consistent with theoretical analysis, hence the effectiveness of the proposed approach is verified. Moreover, the results established in this paper are fairly general and cover the results of some existing papers as special cases, such as, when taking $L = 1$ and $\beta = 1$ (no switching and no actuator faults), the results of this paper reduce to that of the works in [13] and [35]; when taking $L = 1, \beta = 1$, and $C_{r_k,i} = F_{r_k,i} = 0$ (no switching, no actuator faults, and no disturbances), the results of this paper reduce to that of the work in [36].

VI. Conclusion

In this paper, we have investigated SOF control for a class of switched fuzzy systems in the presence of actuator faults. A reliable SOF controller has been designed to ensure the stochastic stability of the closed-loop system and overcome the negative effect caused by actuator faults. The derived conditions are proved to be able to ensure the existence of a feasible controller. Moreover, a prescribed dissipative disturbance attenuation constraint can also be satisfied. Due to the limitations of the traditional singular value decomposition approach, an iterative linearization algorithm is designed to obtain the controller gains. Simulations are carried out to validate and illustrate the theoretical approach. Future work will extend current results to some network induced situations and the algorithm proposed in [37] and [38] may be used in the investigation.

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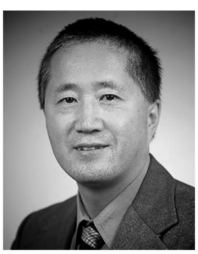

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