International Journal of Control and Automation
Vol.9, No.3 (2016), pp.235-244
http://dx.doi.org/10.14257/ijca.2016.9.3.22

The Delay-Dependent Condition for T-S Fuzzy Lurie Control Systems with Multiple Time-Delays

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Abstract

In this paper, the problem of delay-dependent condition for a new class of Takagi-Sugeno (T-S) fuzzy Lurie control systems with multiple time-delays is discussed. Proper Lyapunov functions are defined by using the Lyapunov stability theory, and a novel delay-dependent absolute stability condition is derived with the linear matrix inequality (LMI) and free-weighting matrix approach, which is different from previous research. Meanwhile, a numerical example is provided to demonstrate feasibility and effectiveness of the proposed result by using the LMI and Simulink toolboxes in MATLAB, and the value of time delay has proved less conservativeness of this method.

Keywords*: T-S fuzzy Lurie systems, Absolute stability, delay-dependent, Multiple time-delays,Lyapunov-Krasovskii functional (LKF), Linear matrix inequality (LMI)*

1. Introduction

Lurie system is a very important nonlinear control system. The majority of nonlinear system can be expressed as the structure of Lurie system, which is connected with the feedback of a linear dynamic system and nonlinear element, and the nonlinear part satisfies a sector condition. As we all know that, the theory of absolute stability has occupied an important place among exact mathematical methods being used in the design and analysis of control systems since the notion of absolute stability was introduced by Lur'e [1]. The absolute stability theory originated from Aizerman and Ganttmacher [2] on the stability analysis of space robot, it plays an important role in the accurate mathematical method for the control system design and analysis. Since the American mathematician Lefschetz [3] proposed clear mathematical formulation for the problem of Lurie in 1965, the absolutely stability theory has been developed rapidly.

In recent years, the stabilization of Lurie systems with time-delay has attracted a large amount of attention [4, 5], as the time-delay phenomenon is frequently encountered in various of engineering systems such as medical system, mechanical system, economy system, long transmission lines and so on. In addition, several novel delay-dependent conditions for absolute stability of Lurie systems with multiple time-delays have been derived [6, 7] based on the Linear matrix inequality (LMI) approach. The advantage of this method is that it uses free weighting matrices to express those relationships.

In 1985, Takagi and Sugeno put forward the famous Takagi-Sugeno (T-S) fuzzy modeling method [8], and provides a new opportunity for development of the study of fuzzy control theory. The main idea of T-S fuzzy system is as to describe a nonlinear system in the form of a weighted sum of some simple linear subsystems, and then the

ISSN: 2005-4297 IJCA

nonlinear system can be stabilized by a model-based fuzzy controller. Therefore, the stability analysis and control synthesis of T-S fuzzy systems with time-delay have attracted the attention of a lot of researchers [9,10] .

However, as far as the authors know, the delay-dependent condition for absolute stability of T-S fuzzy Lurie systems with multiple delays were seldom studied up to now, which motivated our creative passion. In this paper, we set a new T-S fuzzy Lurie control systems. Meanwhile, proper Lyapunov functions are defined and a novel delay-dependent absolutely stable condition is obtained by using the method of Lyapunov functional, Linear matrix inequality (LMI) and free-weighting matrix approach. Meanwhile, a numerical example is provided to demonstrate feasibility and effectiveness of the proposed result.

2. Problem Formulation

The i th rule of the T-S fuzzy model for each $i=1,2,\cdots,r$ is represented as follows:

Plant Rule i: If $s_1(t)$ is M_{i1}, $s_2(t)$ is M_{i2} $,\cdots,s_g(t)$ is M_{ig} THEN

$$\begin{cases} \dot{x}(t)=A_i x(t)+B_i x(t-\tau_i)+D_i u(t)+b_i f(\sigma(t)),\ t\ge 0 \\ \sigma(t)=c^T x(t), \\ x(\theta)=\varphi(\theta), \quad \theta\in\left[-\max\limits_{1\le i\le r}\{\tau_i\},0\right] \end{cases} \tag{1}$$

Where $s_1(t),s_2(t)\cdots,s_g(t)$ are the premise variables, M_{ij} $(j=1,2,\cdots,g)$ is a fuzzy set. $x(t)\in R^n$ denotes the state vector; A_i,B_i,D_i $(i=1,2,\cdots,r)$ are the coefficient matrices with appropriate dimensions; $b_i\in R^n$ is the coefficient of the nonlinearities; $c\in R^n$; $\tau_i\ge 0$ is the time-delay; $\varphi(\cdot)\in C\left[-\max\limits_{1\le i\le r}\{\tau_i\},0\right]$ is a continuous vector valued initial function; the nonlinearity functions $f(\cdot)$ satisfy the following sector condition:

$$f(\cdot)\in K[0,\infty]=\left\{f(\cdot)\mid f(0)=0, 0<\sigma f(\sigma(t))<\infty, \sigma\ne 0\right\} \tag{2}$$

The dynamic fuzzy model can be represented in the following form:

$$\begin{cases} \dot{x}(t)=\sum\limits_{i=1}^{r}h_i(s(t))\left[A_i x(t)+B_i x(t-\tau_i)+D_i u(t)+b_i f(\sigma(t))\right],t\ge 0 \\ \sigma(t)=c^T x(t), \\ x(\theta)=\varphi(\theta), \qquad \theta\in\left[-\max\limits_{1\le i\le r}\{\tau_i\},0\right] \end{cases} \tag{3}$$

where

$$h_i(s(t))=\frac{\omega_i(s(t))}{\sum\limits_{j=1}^{r}\omega_j(s(t))}, \tag{4}$$

$$\omega_i(s(t))=\prod_{j=1}^{g}M_{ij}(s_j(t)), s(t)=\left[s_1(t), s_2(t),\cdots, s_g(t)\right]^T, i=1,2,\cdots,r,$$

in which $M_{ij}\left(s_j\left(t\right)\right)$ is the grade of membership of $s_j\left(t\right)$ in M_{ij}. In this paper, It is assumed that

$$\omega_i\left(s\left(t\right)\right)\geq 0, \sum_{j=1}^{r}\omega_j\left(s\left(t\right)\right)>0, i=1, 2,\cdots,r, \forall t\geq 0.$$

Hence, the fuzzy basis functions satisfy $\sum_{i=1}^{r}h_i\left(s\left(t\right)\right)=1$ with $h_i\left(s\left(t\right)\right)\geq 0,\quad i=1,\cdots,r,\ \ \forall t\geq 0$.

Control rule i :IF $s_1\left(t\right)$ is $M_{i1}\left(t\right), s_2\left(t\right)$ is $M_{i2}\left(t\right),\cdots, s_g\left(t\right)$ is $M_{ig}\left(t\right)$, THEN

$$u\left(t\right)=K_i x\left(t\right),\quad i=1, 2,\cdots,r$$

Where $K_i\in R^{q\times n}\left(i=1, 2,\cdots,r\right)$ is the local controller gain. Using the fuzzy basis functions defined by (4), the overall fuzzy state feedback controller is represented by:

$$u\left(t\right)=\sum_{i=1}^{r}h_i\left(s(t)\right)K_i x\left(t\right)$$

Throughout this paper, we shall use the following lemmas:

Lemma 1. (see [11].) For any constant symmetric matrix R , $M=M^T>0$, scalar $r>0$, vector function $g:\left[0,r\right]\rightarrow R^n$, such that the integrations in the following are well defined, then

$$r\int_0^r g^T\left(s\right)Mg\left(s\right)ds\geq\left[\int_0^r g\left(s\right)ds\right]^T M\left[\int_0^r g\left(s\right)ds\right]$$

Lemma 2. (see Schur complement [12].) Given constant symmetric matrices $\Sigma_1,\Sigma_2,\Sigma_3$ with appropriate dimensions, where $\Sigma_1=\Sigma_1^T$ and $\Sigma_2=\Sigma_2^T$, then $\Sigma_1+\Sigma_3^T\Sigma_2^{-1}\Sigma_3<0$, holds if and only if

$$\begin{bmatrix}\Sigma_1 & \Sigma_3^T\\ \Sigma_3 & -\Sigma_2\end{bmatrix}<0 \text{ or } \begin{bmatrix}-\Sigma_2 & \Sigma_3\\ \Sigma_3^T & \Sigma_1\end{bmatrix}<0$$

3. Main Results

Theorem1. The system (3) is absolutely stable, if there exist matrix $K_i(i=1,2,\cdots,r)$, $\mathrm{S}_l(l=1,2,34)$ and symmetric positive definite matrices $P,Q_k,R_k\left(k=1,2\cdots m\right)$ and scalar $\alpha>0,\ \beta>0,$ such that the following LMIs hold:

$$\mathrm{E}_{ii}=\begin{bmatrix}\Pi_{1ii} & \Pi_2\\ * & \Pi_3\end{bmatrix}<0, i=j, \qquad (5)$$

with

$$\Pi_{1ii}=\begin{bmatrix}\Gamma_{1ii}+\Gamma_{1ii}{}^{T}+W_{1ii} & W_{2ii} & \Gamma_{2i}+W_{3ii} & \Gamma_{3ii}+W_{4ii} & 0\\ * & -S_2{}^{T}-S_2 & S_2{}^{T}B_i-S_3 & S_2{}^{T}b_i-S_4 & 0\\ * & * & Q+S_3{}^{T}B_i+B_i^{T}S_3 & \Gamma_{4i}+S_3{}^{T}b_i+B_i^{T}S_4 & 0\\ * & * & * & 2\beta b_i^{T}c+2S_4{}^{T}b_i & 0\\ * & * & * & * & \bar{R}\end{bmatrix},$$

$$\Pi_2=\begin{bmatrix}Q & \tau_1R_1 & \tau_2R_2 & \cdots & \tau_mR_m\\ 0 & 0 & 0 & \cdots & 0\\ 0 & 0 & 0 & \cdots & 0\\ 0 & 0 & 0 & \cdots & 0\\ 0 & 0 & 0 & \cdots & 0\end{bmatrix}$$

$$\Pi_3=\begin{bmatrix}-Q & 0 & 0 & \cdots & 0\\ * & -R_1 & 0 & \cdots & 0\\ * & * & -R_2 & \cdots & 0\\ * & * & * & \ddots & 0\\ * & * & * & \cdots & -R_m\end{bmatrix},$$

and

$$\mathrm{E}_{ij}=\begin{bmatrix}\Theta_{1ij} & \Theta_2\\ * & \Theta_3\end{bmatrix}<0,\quad 1\le i<j\le r, \qquad (6)$$

$$\Theta_{1ij}=\begin{bmatrix}\Gamma_{1ij}+\Gamma_{1ij}{}^{T}+W_{1ij} & W_{2ij} & \Gamma_{2i}+W_{3ij} & \Gamma_{3ij}+W_{4ij} & 0\\ * & -S_2{}^{T}-S_2 & S_2{}^{T}B_i-S_3 & S_2{}^{T}b_i-S_4 & 0\\ * & * & Q+S_3{}^{T}B_i+B_i^{T}S_3 & \Gamma_{4i}+S_3{}^{T}b_i+B_i^{T}S_4 & 0\\ * & * & * & 2\beta b_i^{T}c+2S_4{}^{T}b_i & 0\\ * & * & * & * & \bar{R}\end{bmatrix}$$

$$\Theta_2=\begin{bmatrix}Q & Q & \tau_1R_1 & \tau_1R_1 & \tau_2R_2 & \tau_2R_2 & \cdots & \tau_mR_m & \tau_mR_m\\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0\end{bmatrix},$$

$$\Theta_3=\begin{bmatrix}-Q & 0 & 0 & 0 & \cdots & 0 & 0\\ * & -Q & 0 & 0 & \cdots & 0 & 0\\ * & * & -R_1 & 0 & \cdots & 0 & 0\\ * & * & * & -R_1 & \cdots & 0 & 0\\ * & * & * & * & \ddots & 0 & 0\\ * & * & * & * & \cdots & -R_m & 0\\ * & * & * & * & \cdots & * & -R_m\end{bmatrix},$$

Let $*$ denotes the elements below the main diagonal of a symmetric block matrix,

$$\Gamma_{1ij} = PA_i + PD_i K_j,$$
$$\Gamma_{2i} = PB_i,$$
$$\Gamma_{3ij} = Pb_i + \beta A_i^T c + \beta K_j^T D_i^T c + \alpha c,$$
$$\Gamma_{4i} = \beta B_i^T c,$$
$$\bar{R} = diag\left[-R_1, -R_2, \cdots, -R_m\right],$$
$$W_{1ij} = S_1^T A_i + A_i^T S_1 + S_1^T D_i K_j + K_j^T D_i^T S_1,$$
$$W_{2ij} = A_i^T S_2 + K_j^T D_i^T S_2 - S_1^T,$$
$$W_{3ij} = S_1^T B_i + A_i^T S_3 + K_j^T D_i^T S_3,$$
$$W_{4ij} = S_1^T b_i + A_i^T S_4 + K_j^T D_i^T S_4,$$
$$\bar{Q} = diag\left[-Q_1, -Q_2, \cdots, -Q_m\right], Q = \sum_{k=1}^{m} Q_k. \qquad \left(1 \le i < j \le r\right).$$

Proof. We use the Lyapunov stability theory and define the Lyapunov-Krasovskii functional candidate as follows:

$$V(t) = V_1(t) + V_2(t) + V_3(t) + V_4(t), \tag{7}$$

where

$$V_1(t) = x^T(t) P x(t),$$
$$V_2(t) = \sum_{k=1}^{m} \int_{t-\tau_k}^{t} x^T(s) Q_k x(s) ds,$$
$$V_3(t) = \sum_{k=1}^{m} \tau_k \int_{-\tau_k}^{0} d\xi \int_{t+\xi}^{t} x^T(s) R_k x(s) ds,$$
$$V_4(t) = 2\beta \int_{0}^{\sigma(t)} f(\sigma) d\sigma.$$

Then, the time derivative of $V(t)$ along the trajectory of system (3) is given by

$$\dot{V}(t) = \dot{V}_1(t) + \dot{V}_2(t) + \dot{V}_3(t) + \dot{V}_4(t), \tag{8}$$

with

$$\begin{aligned}\dot{V}_1(t) &= 2x^T(t) P \dot{x}(t) \\ &= 2\sum_{i=1}^{r} h_i(s(t)) x^T(t) P\left[A_i x(t) + B_i x(t-\tau_i) + D_i u(t) + b_i f(\sigma(t))\right],\end{aligned} \tag{9}$$

$$\dot{V}_2(t) = \sum_{k=1}^{m} x^T(t) Q_k x(t) - \sum_{k=1}^{m} x^T(t-\tau_k) Q_k x(t-\tau_k), \tag{10}$$

$$\dot{V}_3(t) = \sum_{k=1}^{m} \tau_k^2 x^T(t) R_k x(t) - \sum_{k=1}^{m} \int_{t-\tau_k}^{t} x^T(s) \tau_k R_k x(s) ds.$$

By Lemma1, we have

$$\dot{V}_3(t) \le \sum_{k=1}^{m} \tau_k^2 x^T(t) R_k x(t) - \sum_{k=1}^{m} \left[\int_{t-\tau_k}^{t} x(s) ds\right]^T R_k \left[\int_{t-\tau_k}^{t} x(s) ds\right]. \tag{11}$$

Using (1) and (2), the following equation and inequation hold

$$\begin{aligned}\dot{V}_4(t)&=2\beta\dot{\sigma}^T(t)f(\sigma(t))\\&=2\beta\sum_{i=1}^{r}h_i(s(t))\left[A_ix(t)+B_ix(t-\tau_i)+D_iu(t)+b_if(\sigma(t))\right]^T cf(\sigma(t))\\&\le 2\beta\sum_{i=1}^{r}h_i(s(t))\left[A_ix(t)+B_ix(t-\tau_i)+D_iu(t)+b_if(\sigma(t))\right]^T\\&\quad cf(\sigma(t))+2\alpha x^T(t)cf(\sigma(t)).\end{aligned}\tag{12}$$

From (8)~(12), we can obtain

$$\begin{aligned}\dot{V}(t)\le&\sum_{i=1}^{r}h_i(s(t))\Big\{2x^T(t)P\Big[A_ix(t)+B_ix(t-\tau_i)\\&+D_i\sum_{j=1}^{r}h_j(s(t))K_jx(t)+b_if(\sigma(t))\Big]+\sum_{k=1}^{m}x^T(t)Q_kx(t)\\&-\sum_{k=1}^{m}x^T(t-\tau_k)Q_kx(t-\tau_k)+\sum_{k=1}^{m}\tau_k^2x^T(t)R_kx(t)-\sum_{k=1}^{m}\left[\int_{t-\tau_k}^{t}x(s)ds\right]^TR_k\left[\int_{t-\tau_k}^{t}x(s)ds\right]\\&+2\beta\left[A_ix(t)+B_ix(t-\tau_i)+D_i\sum_{j=1}^{r}h_j(s(t))K_jx(t)+b_if(\sigma(t))\right]^Tcf(\sigma(t))\\&+2\alpha x^T(t)cf(\sigma(t))\Big\}+\sum_{i=1}^{r}2h_i(s(t))\left[S_1^Tx^T(t)+S_2^T\dot{x}^T(t)+S_3^Tx^T(t-\tau_i)+S_4^Tf^T(\sigma(t))\right]\\&\left[A_ix(t)+B_ix(t-\tau_i)+D_i\sum_{j=1}^{r}h_j(s(t))K_jx(t)+b_if(\sigma(t))-\dot{x}(t)\right]\\=&\sum_{i=1}^{r}\sum_{j=1}^{r}h_i(s(t))h_j(s(t))\eta^T(t)\Omega_{ij}\eta(t),\end{aligned}\tag{13}$$

here we define:

$$\eta(t)=\left[x^T(t)\quad \dot{x}^T(t)\quad x^T(t-\tau_i)\quad f^T(\sigma(t))\quad E^T(t)\right]^T,$$

$$E(t)=\left[\int_{t-\tau_1}^{t}x^T(s)ds\quad \int_{t-\tau_2}^{t}x^T(s)ds\cdots\int_{t-\tau_m}^{t}x^T(s)ds\right]^T,$$

$$\Omega_{ij}=\begin{bmatrix}\Gamma_{1ij}+\Gamma_{1ij}^T+\sum_{k=1}^{m}(Q_k+\tau_k^2R_k)+W_{1ij} & W_{2ij} & \Gamma_{2i}+W_{3ij} & \Gamma_{3ij}+W_{4ij} & 0\\ * & -S_2^T-S_2 & S_2^TB_i-S_3 & S_2^Tb_i-S_4 & 0\\ * & * & Q+S_3^TB_i+B_i^TS_3 & \Gamma_{4i}+S_3^Tb_i+B_i^TS_4 & 0\\ * & * & * & 2\beta b_i^Tc+2S_4^Tb_i & 0\\ * & * & * & * & \bar{R}\end{bmatrix},\tag{14}$$

where $\Gamma_{1ij},\Gamma_{2i},\Gamma_{3ij}$, $\Gamma_{4i},W_{1ij},W_{2ij},W_{3ij}W_{4ij},\bar{R}(1\le i<j\le r)$ are the same as the corresponding items in inequalities (5) and (6). If $\Omega_{ij}<0$, then there exists a sufficient small scalar $\lambda>0$, such that $\dot{V}(t)\le-\lambda\|x(t)\|^2$ (for $x(t)\ne 0$), which shows that the T-S fuzzy Lurie system with multiple time-delays described by (3) is absolutely stable. Using the Schur complement formula in Lemma2, we know that $\Omega_{ij}<0$ is equivalent to (5) and (6). This completes the proof.

4. Numerical Example

In this example, the T-S fuzzy Lurie system with multiple time-delays considered is with $u(t)=0$ and two rules for $i=j=2$, $m=1$,with $f(\sigma(t))=\tan(\sigma(t))(i=1,2)$, $\tau_1=\tau_2=3$ .The fuzzy basis functions for Rule 1 and Rule 2 are $h_1(s_1(t))=\sin^2(\pi s_1(t))$, $h_2(s_1(t))=\cos^2(\pi s_1(t))$.

Plant Rules.

Rule1: IF $s_1(t)$ is M_{11} Then $\begin{cases}\dot{x}(t)=A_1x(t)+B_1x(t-\tau_1)+b_1f(\sigma(t)), & t\geq 0\\ \sigma(t)=c^Tx(t), \\ x(\theta)=\varphi(\theta), & \theta\in\left[-\max\limits_{1\leq i\leq 2}\{\tau_i\},0\right],\end{cases}$

Rule2: IF $s_1(t)$ is M_{21} Then $\begin{cases}\dot{x}(t)=A_2x(t)+B_2x(t-\tau_2)+b_2f(\sigma(t)), & t\geq 0\\ \sigma(t)=c^Tx(t), \\ x(\theta)=\varphi(\theta), & \theta\in\left[-\max\limits_{1\leq i\leq 2}\{\tau_i\},0\right],\end{cases}$

We suppose

$$A_1=\begin{bmatrix}-1 & 0\\ -1 & -2\end{bmatrix}, A_2=\begin{bmatrix}-2.7 & 1\\ -1 & -1.5\end{bmatrix}, B_1=\begin{bmatrix}-0.1 & -0.5\\ 0.5 & -0.2\end{bmatrix}, B_2=\begin{bmatrix}-0.1 & -0.5\\ 0.4 & -0.1\end{bmatrix},$$
$$b_1=\begin{bmatrix}-0.5\\ -0.3\end{bmatrix}, b_2=\begin{bmatrix}-0.2\\ -0.3\end{bmatrix}, c=\begin{bmatrix}0.4\\ 0.6\end{bmatrix}$$

Using the MATLAB LMI Toolbox, we obtained a set of feasible solutions as follows:

$$P=\begin{bmatrix}1.6283 & -3.3216\\ -3.3216 & 8.1368\end{bmatrix}, Q_1=\begin{bmatrix}1.0211 & -0.0526\\ -0.0526 & 1.1498\end{bmatrix}, R_1=\begin{bmatrix}0.1947 & 0.0459\\ 0.0459 & 0.2567\end{bmatrix},$$
$$S_1=\begin{bmatrix}0.1630 & 2.8624\\ 3.5563 & -6.5427\end{bmatrix}, S_2=\begin{bmatrix}0.5791 & -0.0255\\ 0.0907 & 0.5440\end{bmatrix}, S_3=\begin{bmatrix}-0.0279 & -0.3768\\ 0.2803 & -0.3427\end{bmatrix},$$
$$S_4=\begin{bmatrix}-0.3061\\ -0.4241\end{bmatrix}, \alpha=2.4131, \beta=0.9212.$$

And we use the MATLAB Simulink Toolbox, the state response is shown in Figure 1.

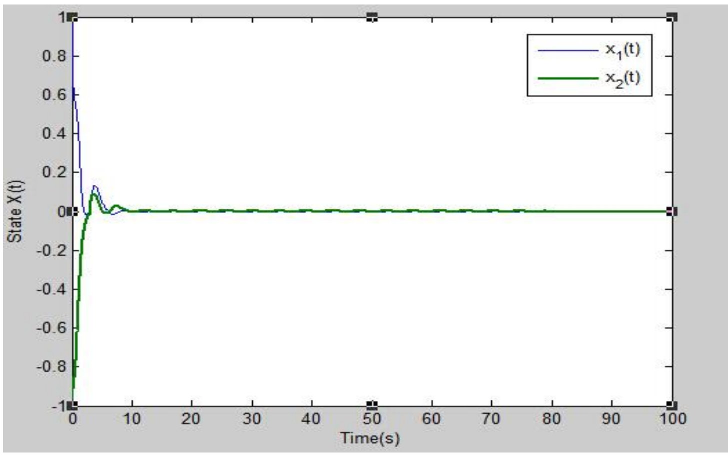

Figure 1. Response of the State $x(t)$

The simulation result in Figure 1 has shown that, under the conditions of Theorem 1, the T-S fuzzy Lurie control system with time-delays is absolutely stabilized.

5. Conclusions

The problem of absolute stability for a class of T-S fuzzy Lurie control systems with multiple time-delays is investigated in this paper. A new system is created by using T-S fuzzy model, which represents a new trend of research for Lurie control system. Using the Lyapunov-Krasovskii functional (LKF), the linear matrix inequality (LMI) and free-weighting matrix approach, a new delay-dependent condition for such systems is obtained and described in the form of LMI, which is different from previous studies. Finally, the result of numerical example has shown that the proposed results are feasible and effective, and the value of time delay has proved less conservativeness of this method.

Acknowledgements

This project is supported by 2015 Scientific Research Fund of SiChuan Provincial Education Department (the research and practice of multidimensional dynamic teaching evaluation and management system of higher learning institutions based on the fuzzy math-ematical model, 15SB0039).

This work is also supported by Research of multi campus information security under the background of the Central Plains Economic Region, Science and Technology Department of Henan Province scientific and technological project (142102310096).

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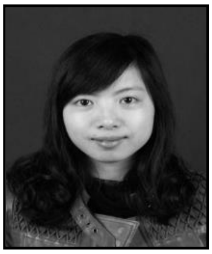

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