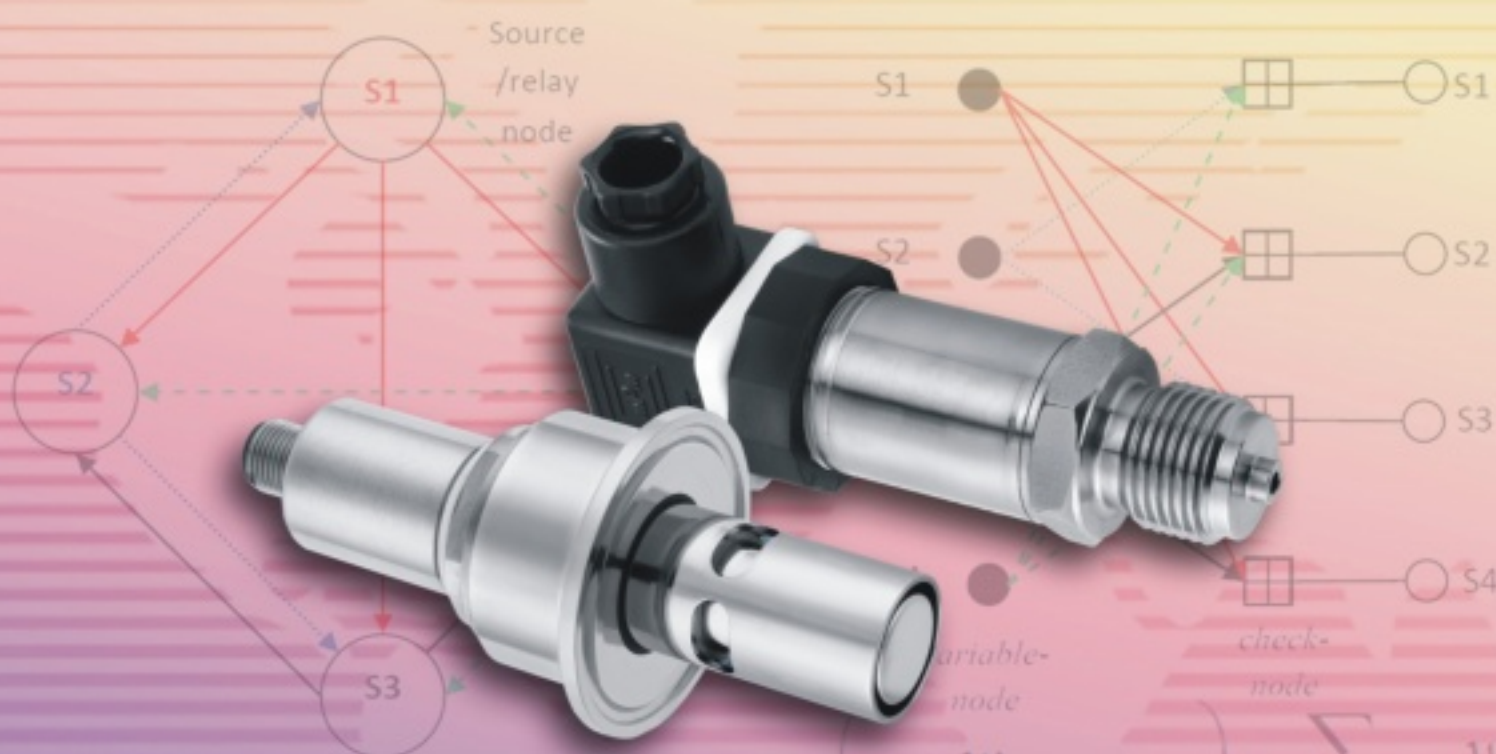


SENSORS & TRANSDUCERS

ISSN 1726-5479

vol. 20
Special

4/13



Sensors, Networks, Control Systems and Information Processing

Sensors & Transducers

**International Official Journal of the International
Frequency Sensor Association (IFSA) Devoted to
Research and Development of Sensors and Transducers**

Volume 20, Special Issue, April 2013

Editor-in-Chief
Sergey Y. YURISH



IFSA Publishing: Barcelona • Toronto

Copyright © 2013 IFSA Publishing. All rights reserved.

This journal and the individual contributions in it are protected under copyright by IFSA Publishing, and the following terms and conditions apply to their use:

Photocopying: Single photocopies of single articles may be made for personal use as allowed by national copyright laws. Permission of the Publisher and payment of a fee is required for all other photocopying, including multiple or systematic copyright, copyright for advertising or promotional purposes, resale, and all forms of document delivery.

Derivative Works: Subscribers may reproduce tables of contents or prepare list of articles including abstract for internal circulation within their institutions. Permission of the Publisher is required for resale or distribution outside the institution.

Permission of the Publisher is required for all other derivative works, including compilations and translations.

Authors' copies of Sensors & Transducers journal and articles published in it are for personal use only.

Address permissions requests to: IFSA Publisher by e-mail: editor@sensorsportal.com

Notice: No responsibility is assumed by the Publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein.

Printed in the USA.



Sensors & Transducers

Volume 20, Special Issue,
April 2013

www.sensorsportal.com

ISSN 2306-8515
e-ISSN 1726-5479

Editors-in-Chief: professor Sergey Y. Yurish,
Tel.: +34 696067716, e-mail: editor@sensorsportal.com

Editors for Western Europe

Meijer, Gerard C.M., Delft Univ. of Technology, The Netherlands
Ferrari, Vittorio, Università di Brescia, Italy

Editor for Eastern Europe

Sachenko, Anatoly, Ternopil National Economic University, Ukraine

Editors for North America

Katz, Evgeny, Clarkson University, USA
Datskos, Panos G., Oak Ridge National Laboratory, USA
Fabien, J. Josse, Marquette University, USA

Editor South America

Costa-Felix, Rodrigo, Inmetro, Brazil

Editors for Asia

Ohyama, Shinji, Tokyo Institute of Technology, Japan
Zhengbing, Hu, Huazhong Univ. of Science and Technol., China

Editor for Asia-Pacific

Mukhopadhyay, Subhas, Massey University, New Zealand

Editor for Africa

Maki K.Habib, American University in Cairo, Egypt

Editorial Board

Abdul Rahim, Ruzairi, Universiti Teknologi, Malaysia
Abramchuk, George, Measur. Tech. & Advanced Applications, Canada
Ascoli, Giorgio, George Mason University, USA
Atalay, Selcuk, Inonu University, Turkey
Atghiaee, Ahmad, University of Tehran, Iran
Augutis, Vygtantas, Kaunas University of Technology, Lithuania
Ayesh, Aladdin, De Montfort University, UK
Baliga, Shankar, B., General Monitors, USA
Basu, Sukumar, Jadavpur University, India
Bousbia-Salah, Mounir, University of Annaba, Algeria
Bouvet, Marcel, University of Burgundy, France
Campanella, Luigi, University La Sapienza, Italy
Carvalho, Vitor, Minho University, Portugal
Changhai, Ru, Harbin Engineering University, China
Chen, Wei, Hefei University of Technology, China
Cheng-Ta, Chiang, National Chia-Yi University, Taiwan
Chung, Wen-Yaw, Chung Yuan Christian University, Taiwan
Cortes, Camilo A., Universidad Nacional de Colombia, Colombia
D'Amico, Arnaldo, Università di Tor Vergata, Italy
De Stefano, Luca, Institute for Microelectronics and Microsystem, Italy
Ding, Jianning, Changzhou University, China
Djordjevich, Alexander, City University of Hong Kong, Hong Kong
Donato, Nicola, University of Messina, Italy
Dong, Feng, Tianjin University, China
Erkmen, Aydan M., Middle East Technical University, Turkey
Gaura, Elena, Coventry University, UK
Gole, James, Georgia Institute of Technology, USA
Gong, Hao, National Institute of Singapore, Singapore
Gonzalez de la Rosa, Juan Jose, University of Cadiz, Spain
Guillet, Bruno, University of Caen, France
Hadjiloucas, Sillas, The University of Reading, UK
Hao, Shiyong, Michigan State University, USA
Hui, David, University of New Orleans, USA
Jaffrezic-Renault, Nicole, Claude Bernard University Lyon 1, France
Jamil, Mohammad, Qatar University, Qatar
Kaniusas, Eugenijus, Vienna University of Technology, Austria
Kim, Min Young, Kyungpook National University, Korea
Kumar, Arun, University of Delaware, USA
Lay-Ekuakille, Aime, University of Lecce, Italy
Li, Si, GE Global Research Center, USA
Lin, Paul, Cleveland State University, USA
Liu, Aihua, Chinese Academy of Sciences, China

Mahadi, Muhammad, University Tun Hussein Onn Malaysia, Malaysia
Mansor, Muhammad Naufal, University Malaysia Perlis, Malaysia
Marquez, Alfredo, Centro de Investigacion en Materiales Avanzados, Mexico
Mishra, Vivekanand, National Institute of Technology, India
Moghavvemi, Mahmoud, University of Malaya, Malaysia
Morello, Rosario, University "Mediterranea" of Reggio Calabria, Italy
Mulla, Intiaz Sirajuddin, National Chemical Laboratory, Pune, India
Nabok, Aleksey, Sheffield Hallam University, UK
Neshkova, Milka, Bulgarian Academy of Sciences, Bulgaria
Passaro, Vittorio M. N., Politecnico di Bari, Italy
Penza, Michele, ENEA, Italy
Pereira, Jose Miguel, Instituto Politecnico de Setebal, Portugal
Pogacnik, Lea, University of Ljubljana, Slovenia
Pullini, Daniele, Centro Ricerche FIAT, Italy
Reig, Candid, University of Valencia, Spain
Restivo, Maria Teresa, University of Porto, Portugal
Rodríguez Martínez, Angel, Universidad Politécnica de Cataluña, Spain
Sadana, Ajit, University of Mississippi, USA
Sadeghian Marnani, Hamed, TU Delft, The Netherlands
Sapozhnikova, Ksenia, D. I. Mendeleev Institute for Metrology, Russia
Singhal, Subodh Kumar, National Physical Laboratory, India
Shah, Kriyang, La Trobe University, Australia
Shi, Wendian, California Institute of Technology, USA
Shmaliy, Yuriy, Guanajuato University, Mexico
Song, Xu, An Yang Normal University, China
Srivastava, Arvind K., LightField, Corp, USA
Stefanescu, Dan Mihai, Romanian Measurement Society, Romania
Sumriddetchkajorn, Sarun, Nat. Electr. & Comp. Tech. Center, Thailand
Sun, Zhiqiang, Central South University, China
Sysoev, Victor, Saratov State Technical University, Russia
Thirunavukkarasu, I., Manipal University Karnataka, India
Tianxing, Chu, Research Center for Surveying & Mapping, Beijing, China
Vazquez, Carmen, Universidad Carlos III Madrid, Spain
Wang, Jiangping, Xian Shiyong University, China
Xue, Ning, Agiltron, Inc., USA
Yang, Dongfang, National Research Council, Canada
Yang, Shuang-Hua, Loughborough University, UK
Yaping Dan, Harvard University, USA
Zakaria, Zulkarnay, University Malaysia Perlis, Malaysia
Zhang, Weiping, Shanghai Jiao Tong University, China
Zhang, Wenming, Shanghai Jiao Tong University, China

Contents

Volume 20
Special Issue
April 2013

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Application of Partial Least Squares Regression to Static Magnetic Grid Displacement Sensor <i>Qiao Shuang</i>	1
A Fast Responsive Refractometer Based on the Side-opened, Dual-core Photonic Crystal Fiber <i>Jiang Jianhu, Jiao Wentan, Song Lijun</i>	6
Code-Folding Scheme for Energy Efficient Cooperative Communications in Wireless Sensor Networks <i>Zhenbang Wang, Zhenyong Wang, Xuemai Gu</i>	12
A New Missing Values Estimation Algorithm in Wireless Sensor Networks Based on Convolution <i>Feng Liu</i>	21
Heterogeneous Network Convergence with Artificial Mapping for Cognitive Radio Networks <i>Hang Qin, Jun Su, Zhengbing Hu</i>	27
An Improved Phase-Coherent Algorithm for High Dynamic Doppler Simulation in Navigation Simulator <i>Qi Wei, Guo Junhai, Liu Guangjun, Luo Haiying, Wang Jing</i>	37
Implementation of Closed Loop Control System of FOG Based on FPGA <i>Q. D. Sun, Z. H. Zhu and B. P. Larouche</i>	46
Decentralized Robust Control for Nonlinear Interconnected Systems Based on T-S Fuzzy Bilinear Model <i>Zhang Guo and Zhao Yanhua</i>	53
The Formation of the Local Gravitational Model Based on Point-mass Method <i>Wang Jian-Qiang, Zhao Guo-Qiang, Yu Zhi-Qi</i>	64
Sliding Mode Tracking Control of Manipulator Based on the Improved Reaching Law <i>Wei-Na Zhai, Yue-Wang Ge, Shu-Zhong Song, Yan Wang</i>	69
The Study of Elderly Informational Education under “Cloud Computing” <i>Fan ChangXing</i>	79

Authors are encouraged to submit article in MS Word (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com
Please visit journal's webpage with preparation instructions: <http://www.sensorsportal.com/HTML/DIGEST/Submission.htm>



The Fourth International Conference on Sensor Device Technologies and Applications

SENSORDEVICES 2013

25 - 31 August 2013 - Barcelona, Spain

Tracks: Sensor devices - Ultrasonic and Piezosensors - Photonics - Infrared - Gas Sensors - Geosensors - Sensor device technologies - Sensors signal conditioning and interfacing circuits - Medical devices and sensors applications - Sensors domain-oriented devices, technologies, and applications - Sensor-based localization and tracking technologies - Sensors and Transducers for Non-Destructive Testing

Deadline for papers: 30 March 2013

<http://www.iaia.org/conferences2013/SENSORDEVICES13.html>



The Seventh International Conference on Sensor Technologies and Applications

**Deadline for papers:
30 March 2013**

SENSORCOMM 2013

25 - 31 August 2013 - Barcelona, Spain

Tracks: Architectures, protocols and algorithms of sensor networks - Energy, management and control of sensor networks - Resource allocation, services, QoS and fault tolerance in sensor networks - Performance, simulation and modelling of sensor networks - Security and monitoring of sensor networks - Sensor circuits and sensor devices - Radio issues in wireless sensor networks - Software, applications and programming of sensor networks - Data allocation and information in sensor networks - Deployments and implementations of sensor networks - Under water sensors and systems - Energy optimization in wireless sensor networks

<http://www.iaia.org/conferences2013/SENSORCOMM13.html>



The Sixth International Conference on Advances in Circuits, Electronics and Micro-electronics

CENICS 2013

25 - 31 August 2013 - Barcelona, Spain

Deadline for papers: 30 March 2013

Tracks: Semiconductors and applications - Design, models and languages - Signal processing circuits - Arithmetic computational circuits - Microelectronics - Electronics technologies - Special circuits - Consumer electronics - Application-oriented electronics

<http://www.iaia.org/conferences2013/CENICS13.html>

Decentralized Robust Control for Nonlinear Interconnected Systems Based on T-S Fuzzy Bilinear Model

Zhang Guo and Zhao Yanhua

Electrical Engineering Department, Luoyang Institute of Science and Technology,
471023, Luoyang P. R. China

Received: 21 January 2013 / Accepted: 17 April 2013 / Published: 30 April 2013

Abstract: This paper focuses on the decentralized robust control problem for a class of nonlinear interconnected systems which are composed by Takagi-Sugeno (T-S) fuzzy bilinear models with interconnections. Based on the Lyapunov stability analysis theory, some robust stabilization sufficient conditions are derived for the whole closed-loop fuzzy interconnected systems. The corresponding decentralized fuzzy controller design is converted into a convex optimization problem with linear matrix inequality (LMI) constraints. The simulation examples show the effectiveness of the proposed approach. *Copyright © 2013 IFSA.*

Keywords: Fuzzy control, Decentralized control, Robust stabilization, Fuzzy bilinear model, Linear matrix inequality (LMI).

1. Introduction

In recent years, T-S model-based fuzzy control has attracted wide attention, essentially because the fuzzy model is an effective and flexible tool for control of nonlinear systems [1, 2]. The T-S fuzzy model is employed to represent or approximate a nonlinear system, which is described by a family of fuzzy IF-THEN rules that represent local linear input-output relations of the system. The overall fuzzy model of the system is achieved by smoothly blending these local linear models together through membership functions. The control design is carried out based on the fuzzy model via the so-called parallel distributed compensation (PDC) scheme [2]. The idea is that for each local linear model, a linear feedback control is designed and the resulting overall controller, which is nonlinear in general, is fuzzy blending of each individual linear controller. Just because of this, T-S

fuzzy model is widely used to the control design of nonlinear systems.

Large-scale interconnected systems can be found in many real-life practical applications such as electric power systems, nuclear reactors, economic systems, process control systems, computer networks, and urban traffic networks, etc. The properties of interconnected systems have been widely studied and many different approaches have been proposed to stabilize the interconnected linear systems [3, 4]. At the same time, T-S fuzzy model is widely used to the control design of nonlinear interconnected systems [5, 6]. However, it is noted that the above nonlinear interconnected systems are all based on T-S fuzzy linear model.

It is known that bilinear system can describe many physical systems and dynamical processes in engineering fields [7, 8]. There are two main advantages of the bilinear system. One is that it provides a better approximation to a nonlinear system

than a linear one. Another is that many real physical processes may be appropriately modeled as bilinear systems when the linear models are inadequate. A good example of a bilinear system is the population of biological species described by $\frac{d\theta}{dt} = \theta v$, where v is

the birth rate minus death rate, and θ denotes the population. It is impossible to approximate the aforementioned equation by a linear model [7].

Most of the existing results focus on the stability analysis and synthesis based on T-S fuzzy model with linear local model. However, when a nonlinear system has complex nonlinearities, the constructed T-S model will have to consist of a number of fuzzy local models. This will lead to very heavy computational burden. Considering the advantages of bilinear systems and T-S fuzzy control, the fuzzy system based on the T-S fuzzy model with bilinear rule consequence was attracted the interest of researchers [8-13]. The fuzzy bilinear model may be suitable for some classes of nonlinear plants [8]. The robust stabilization for continuous-time fuzzy system with bilinear model was studied in [8], then the result was extended to the delay fuzzy system [9]. The problem of robust stabilization for discrete-time fuzzy system with bilinear model was investigated in [10]. In [11], we extended the idea in [8] to multiple input bilinear systems with uncertainties, and proposed a robust H-infinity control strategy. We also obtained the non-fragile control law for the fuzzy systems with bilinear model in [12]. So far, the decentralized control of fuzzy interconnected systems with bilinear model has not been discussed.

2. System Description and Assumptions

Consider a nonlinear interconnected large-scale system Ω composed of S subsystems $\Omega_i, i = 1, 2, \dots, S$. Each fuzzy rule of the subsystem Ω_i can be represented by the T-S bilinear model. The m -th rule for the subsystem Ω_i is proposed as the following form:

$$\begin{aligned} R_i^m \text{ if } \xi_{i1}(t) \text{ is } F_{i1}^m \text{ and } \dots \text{ and } \xi_{iv_i}(t) \text{ is } F_{iv_i}^m \\ \text{then } \dot{x}_i(t) = (A_{im} + \Delta A_{im})x_i(t) + (N_{im} + \Delta N_{im})x_i(t)u_i(t) + (B_{im} + \Delta B_{im})u_i(t) \\ + \sum_{j=1, j \neq i}^S (C_{jim} + \Delta C_{jim})x_j(t) \quad m = 1, 2, \dots, r_i \end{aligned} \quad (1)$$

where r_i is the number of the fuzzy rules for the i -th subsystem. $\xi_{ij}(t)$ and $F_{ij}^m, j = 1, 2, \dots, v_i$ are some measurable premise variables and fuzzy sets. $x_i(t) \in R^{n_i}, u_i(t) \in R$ are the state vector and control input of the subsystem, respectively. $A_{im} \in R^{n_i \times n_i}, B_{im} \in R^{n_i \times 1}, N_{im} \in R^{n_i \times n_i}$ denote the subsystem matrices with appropriate dimensions. $C_{jim} \in R^{n_i \times n_j}$ represents the interconnection matrix between the i -th and the j -th subsystems. $\Delta A_{im}, \Delta B_{im}, \Delta N_{im}$ and ΔC_{jim} are real bounded matrices containing time-varying parameter uncertainties. We assume, as usual, that the uncertainties should satisfy the following assumption.

Assumption 1 [8]: The parameter uncertainties considered here are norm-bounded and presented by the form

$$[\Delta A_{im} \quad \Delta N_{im} \quad \Delta B_{im}] = H_{im} F_{im}(t) [E_{i1m} \quad E_{i2m} \quad E_{i3m}]$$

Motivated by the above observation, in this paper, the problem of decentralized robust control is studied for the interconnected systems with fuzzy local bilinear model. Based on the PDC scheme, new robust stabilization conditions for the closed-loop fuzzy systems are derived. The three main contributions of this paper are the following: 1) The fuzzy bilinear model is extended to the interconnected nonlinear systems; 2) A decentralized controller is presented for the fuzzy interconnected system with uncertainties in state, input and interconnected term; 3) The decentralized robust stability conditions for the fuzzy system are described by LMIs. Finally, two simulation examples are given to demonstrate the results

The paper is organized as follows. Section 2 introduces the fuzzy interconnected system with local bilinear model and decentralized robust controller law for such system. Results of decentralized robust control are given in Section 3. Two simulation examples are used to illustrate the effectiveness of the proposed method in Section 4, which is followed by conclusions in Section 5.

Notation 1: Throughout this paper, a real symmetric matrix $P > 0 (P \geq 0)$ denotes P being a positive definite (or positive semi-definite) matrix. In symmetric block matrices, we use an asterisk (*) to represent a term that is induced by symmetry and $diag\{\dots\}$ stands for a block-diagonal matrix. The notion $\sum_{i,j=1}^s$ means $\sum_{i=1}^s \sum_{j=1}^s$. Matrices, if the dimensions are not explicitly stated, are assumed to have compatible dimensions for algebraic operations.

$$\Delta C_{jim} = Y_{jim} F_{jim}(t) T_{jim},$$

where $E_{i1m}, E_{i2m}, E_{i3m}, H_{im}, Y_{jim}, T_{jim}$ are known real constant matrices of appropriate dimension, and $F_{im}(t), F_{jim}(t)$ are unknown matrix functions with Lebesgue-measurable elements and satisfies $F_{im}^T(t)F_{im}(t) \leq I, F_{jim}^T(t)F_{jim}(t) \leq I$ for all t .

By using singleton fuzzifier, product inferred, and weighted defuzzifier, the system can be expressed by the following global model:

$$\dot{x}_i(t) = \sum_{m=1}^{r_i} h_{im}(\xi_i(t)) [(A_{im} + \Delta A_{im})x_i(t) + (N_{im} + \Delta N_{im})x_i(t)u_i(t) + (B_{im} + \Delta B_{im})u_i(t) + \sum_{j=1, j \neq i}^S (C_{jim} + \Delta C_{jim})x_j(t)], \quad (2)$$

where $h_{im}(\xi_i(t)) = \frac{\omega_{im}(\xi_i(t))}{\sum_{m=1}^{r_i} \omega_{im}(\xi_i(t))}$, $\omega_{im}(\xi_i(t)) = \prod_{j=1}^{v_i} \mu_{imj}(\xi_i(t))$. $\mu_{imj}(\xi_i(t))$ is the grade of membership of $\xi_{ij}(t)$ in F_{ij}^m . In this paper, it is assumed that $\omega_{im}(\xi_i(t)) \geq 0$ and $\sum_{m=1}^{r_i} \omega_{im}(\xi_i(t)) > 0$ for all t . Then we have the following conditions $h_{im}(\xi_i(t)) \geq 0$ and $\sum_{m=1}^{r_i} h_{im}(\xi_i(t)) = 1$ for all t . In what follows, we will drop the argument of $h_{im}(\xi_i(t))$ for simplicity.

Based on PDC, the fuzzy controller shares the same premise parts with (1), the i -th fuzzy controller is formulated as follow

$$\begin{aligned} & \text{if } \xi_{i1}(t) \text{ is } F_{i1}^m \text{ and } \dots \text{ and } \xi_{iv_i}(t) \text{ is } F_{iv_i}^m \\ & \text{then } u_i(t) = \frac{\rho_i K_{im} x_i(t)}{\sqrt{1 + x_i^T K_{im}^T K_{im} x_i}} = \rho_i \sin \theta_{im} = \rho_i \cos \theta_{im} K_{im} x_i(t) \end{aligned} \quad (3)$$

where $K_{im} \in R^{1 \times n_i}$ is a local controller gain to be determined and $\rho_i > 0$ is a scalar to be assigned.

$$\sin \theta_{im} = \frac{K_{im} x_i(t)}{\sqrt{1 + x_i^T K_{im}^T K_{im} x_i}}, \cos \theta_{im} = \frac{1}{\sqrt{1 + x_i^T K_{im}^T K_{im} x_i}}, \theta_{im} \in [-\frac{\pi}{2}, \frac{\pi}{2}],$$

$m = 1, 2, \dots, r_i, i = 1, 2, \dots, S$.

The overall fuzzy control law can be represented by

$$u_i(t) = \sum_{m=1}^{r_i} h_{im} \rho_i \sin \theta_{im} = \sum_{m=1}^{r_i} h_{im} \rho_i \cos \theta_{im} K_{im} x_i(t) \quad (4)$$

By substituting (4) into (2), the i -th closed-loop subsystem can be represented as

$$\dot{x}_i(t) = \sum_{m,n=1}^{r_i} h_{im} h_{in} [(\Lambda_{i,mn} + \Delta \Lambda_{i,mn})x_i(t) + \sum_{j=1, j \neq i}^S (C_{jim} + \Delta C_{jim})x_j(t)], \quad (5)$$

where $\Lambda_{i,mn} = A_{im} + \rho_i \sin \theta_{in} N_{im} + \rho_i \cos \theta_{in} B_{in} K_{in}$, $\Delta \Lambda_{i,mn} = \Delta A_{im} + \rho_i \sin \theta_{in} \Delta N_{im} + \rho_i \cos \theta_{in} \Delta B_{in} K_{in}$.

The objective of the paper is to design decentralized fuzzy controllers (4) such that the closed-loop systems (5) is decentralized robust stable.

3. Main Results

Before proceeding with the following theorems, we introduce the following lemmas which will be used in our results.

Lemma 1 [14]: Given any matrices M and N with appropriate dimensions such that $\varepsilon > 0$, we have

$$M^T N + N^T M \leq \varepsilon M^T M + \varepsilon^{-1} N^T N.$$

Lemma 2 [15]: Let M, N and $F(t)$ be real matrices of appropriate dimensions with $F(t)^T F(t) \leq I$. For scalar $\varepsilon > 0$, we have $M^T F(t)N + N^T F^T(t)M \leq \varepsilon M^T M + \varepsilon^{-1} N^T N$.

The following theorem gives the sufficient condition for the existence of the fuzzy decentralized controller for the interconnected system (5).

Theorem 1 For given scalars $\rho_i > 0, \varepsilon_{1i} > 0, \varepsilon_{2i} > 0, \varepsilon_{3i} > 0, i = 1, 2, \dots, S$, the interconnect system (5) is robust stable if there exist positive definite matrices $P_i > 0, i = 1, 2, \dots, S$ and matrices $K_{im}, m = 1, 2, \dots, r_i, i = 1, 2, \dots, S$ such that the following inequalities (6)-(7) are satisfied.

$$\Phi_{i,mm} < 0, \quad m = 1, 2, \dots, r_i, \quad i = 1, 2, \dots, S \quad (6)$$

$$\Phi_{i,mm} + \Phi_{i,nn} < 0, \quad 1 \leq m < n \leq r_i, \quad i = 1, 2, \dots, S, \quad (7)$$

where

$$\begin{aligned} \Phi_{i,mm} &= \phi_{i,mm} + \sum_{j=1, j \neq i}^S P_i C_{jim} C_{jim}^T P_i + (S-1)I + \sum_{j=1, j \neq i}^S P_i Y_{jim} Y_{jim}^T P_i + \sum_{j=1, j \neq i}^S T_{ijm}^T T_{ijm}, \\ \phi_{i,mm} &= A_{im}^T P_i + P_i A_{im} + \varepsilon_{1i} \rho_i^2 P_i P_i + \varepsilon_{1i}^{-1} N_{im}^T N_{im} + \varepsilon_{1i}^{-1} (B_{im} K_{in})^T (B_{im} K_{in}) + \varepsilon_{2i}^{-1} E_{i1m}^T E_{i1m} \\ &\quad + (\varepsilon_{2i} + \varepsilon_{3i} \rho_i^2) P_i H_{im} H_{im}^T P_i + \varepsilon_{3i}^{-1} E_{i2m}^T E_{i2m} + \varepsilon_{3i}^{-1} (E_{i3m} K_{in})^T (E_{i3m} K_{in}). \end{aligned}$$

Proof: Take the Lyapunov function candidate as

$$V(t) = \sum_{i=1}^S V_i(t) = \sum_{i=1}^S x_i^T(t) P_i x_i(t) \quad (8)$$

The time derivatives of $V(t)$, along the trajectory of the system (5) is given by

$$\begin{aligned} \dot{V}(t) &= \sum_{i=1}^S [\dot{x}_i^T(t) P_i x_i(t) + x_i^T(t) P_i \dot{x}_i(t)] \\ &= \sum_{i=1}^S \sum_{m=1}^{r_i} h_m h_m [x_i^T(t) (\Lambda_{i,mm}^T P_i + P_i \Lambda_{i,mm} + \Delta \Lambda_{i,mm}^T P_i + P_i \Delta \Lambda_{i,mm}) x_i(t) \\ &\quad + \sum_{j=1, j \neq i}^S x_j^T(t) C_{jim}^T P_i x_i(t) + x_i^T(t) P_i \sum_{j=1, j \neq i}^S C_{jim} x_j(t) \\ &\quad + \sum_{j=1, j \neq i}^S x_j^T(t) \Delta C_{jim}^T P_i x_i(t) + x_i^T(t) P_i \sum_{j=1, j \neq i}^S \Delta C_{jim} x_j(t)] \end{aligned} \quad (9)$$

Applying Lemma 1, we have the following inequalities

$$\begin{aligned} \Lambda_{i,mm}^T P_i + P_i \Lambda_{i,mm} &\leq A_{im}^T P_i + P_i A_{im} + \varepsilon_{1i} \rho_i^2 P_i P_i + \varepsilon_{1i}^{-1} N_{im}^T N_{im} + \varepsilon_{1i}^{-1} (B_{im} K_{in})^T (B_{im} K_{in}), \\ \sum_{i=1}^S \sum_{m=1}^{r_i} h_m [&\sum_{j=1, j \neq i}^S x_j^T(t) C_{jim}^T P_i x_i(t) + x_i^T(t) P_i \sum_{j=1, j \neq i}^S C_{jim} x_j(t)] \\ &\leq \sum_{i=1}^S \sum_{m=1}^{r_i} h_m [x_i^T(t) P_i \sum_{j=1, j \neq i}^S C_{jim} C_{jim}^T P_i x_i(t) + \sum_{j=1, j \neq i}^S x_j^T(t) x_j(t)] \\ &= \sum_{i=1}^S \sum_{m=1}^{r_i} h_m [x_i^T(t) P_i \sum_{j=1, j \neq i}^S C_{jim} C_{jim}^T P_i x_i(t) + (S-1) x_i^T(t) x_i(t)]. \end{aligned} \quad (10)$$

Similar, applying Lemma 2, we get

$$\begin{aligned}
 \Delta\Lambda_{i,mn}^T P_i + P_i \Delta\Lambda_{i,mn} &\leq \varepsilon_{2i} P_i H_{im} H_{im}^T P_i + \varepsilon_{2i}^{-1} E_{i1m}^T E_{i1m} + \varepsilon_{3i} \rho_i^2 P_i H_{im} H_{im}^T P_i \\
 &\quad + \varepsilon_{3i}^{-1} E_{i2m}^T E_{i2m} + \varepsilon_{3i}^{-1} (E_{i3m} K_{in})^T (E_{i3m} K_{in}), \\
 \sum_{i=1}^S \sum_{m=1}^{r_i} h_{im} &[\sum_{j=1, j \neq i}^S x_j^T(t) \Delta C_{jim}^T P_i x_i(t) + x_i^T(t) P_i \sum_{j=1, j \neq i}^S \Delta C_{jim} x_j(t)] \\
 &\leq \sum_{i=1}^S \sum_{m=1}^{r_i} h_{im} [x_i^T(t) P_i \sum_{j=1, j \neq i}^S Y_{jim} Y_{jim}^T P_i x_i(t) + x_j^T(t) \sum_{j=1, j \neq i}^S T_{jim}^T T_{jim} x_j(t)] \\
 &= \sum_{i=1}^S \sum_{m=1}^{r_i} h_{im} [x_i^T(t) P_i \sum_{j=1, j \neq i}^S Y_{jim} Y_{jim}^T P_i x_i(t) + x_i^T(t) \sum_{j=1, j \neq i}^S T_{ijm}^T T_{ijm} x_i(t)].
 \end{aligned} \tag{11}$$

Then, substituting (10) and (11) into (9) yields

$$\begin{aligned}
 \dot{V}(t) &\leq \sum_{i=1}^S \sum_{m,n=1}^{r_i} h_{im} h_{in} x_i^T(t) \Phi_{i,mn} x_i(t) \\
 &= \sum_{i=1}^S \sum_{m=1}^{r_i} h_{im}^2 x_i^T(t) \Phi_{i,mn} x_i(t) + \sum_{i=1}^S \sum_{1=m < n}^{r_i} h_{im} h_{in} x_i^T(t) (\Phi_{i,mn} + \Phi_{i,nm}) x_i(t)
 \end{aligned} \tag{12}$$

Therefore, it is noted that (6) and (7) imply $\dot{V}(t) < 0$, so the interconnected system (5) is robust stable. Thus, we complete the proof.

It is noted that the matrix inequalities (6)-(7) are nonlinear matrix inequalities. In the following theorem, we will derive a sufficient condition such that the matrix inequalities (6)-(7) can be transformed into an LMI problem.

Theorem 2 For given scalars $\rho_i > 0, \varepsilon_{1i} > 0, \varepsilon_{2i} > 0, \varepsilon_{3i} > 0, i = 1, 2, \dots, S$, the interconnect system (5) is robust stability if there exist positive definite matrices $Z_i > 0, i = 1, 2, \dots, S$ and matrices $G_{im}, i = 1, 2, \dots, S; m = 1, 2, \dots, r_i$ such that the matrix inequalities (13)-(14) are satisfied. Moreover, the feedback gains are given by $K_{im} = G_{im} Z_i^{-1}, i = 1, 2, \dots, S; m = 1, 2, \dots, r_i$.

$$\begin{bmatrix}
 \varphi_{i,m} & * & * & * & * & * & * & * \\
 Z_i & -\frac{I}{S-1} & * & * & * & * & * & * \\
 N_{im} Z_i & 0 & -\varepsilon_{1i} I & * & * & * & * & * \\
 B_{im} G_{im} & 0 & 0 & -\varepsilon_{1i} I & * & * & * & * \\
 E_{i1m} Z_i & 0 & 0 & 0 & -\varepsilon_{2i} I & * & * & * \\
 E_{i2m} Z_i & 0 & 0 & 0 & 0 & -\varepsilon_{3i} I & * & * \\
 E_{i3m} G_{im} & 0 & 0 & 0 & 0 & 0 & -\varepsilon_{3i} I & * \\
 \overline{TZ}_{i,m} & 0 & 0 & 0 & 0 & 0 & 0 & -I
 \end{bmatrix} < 0, \tag{13}$$

$i = 1, 2, \dots, S; \quad m = 1, 2, \dots, r_i.$

$$\begin{bmatrix}
 \varphi_{i,m} + \varphi_{i,n} & * & * & * & * & * & * & * \\
 2Z_i & -\frac{2I}{S-1} & * & * & * & * & * & * \\
 \overline{NZ}_{i,mn} & 0 & -\varphi_{33} & * & * & * & * & * \\
 \overline{BG}_{i,mn} & 0 & 0 & -\varphi_{44} & * & * & * & * \\
 \overline{E_1 Z}_{i,mn} & 0 & 0 & 0 & -\varphi_{55} & * & * & * \\
 \overline{E_2 Z}_{i,mn} & 0 & 0 & 0 & 0 & -\varphi_{66} & * & * \\
 \overline{E_3 G}_{i,mn} & 0 & 0 & 0 & 0 & 0 & -\varphi_{77} & * \\
 \overline{TZ}_{i,mn} & 0 & 0 & 0 & 0 & 0 & 0 & -I
 \end{bmatrix} < 0, \tag{14}$$

$i = 1, 2, \dots, S; \quad 1 \leq m < n \leq r_i.$

where

$$\begin{aligned}
 \varphi_{i,m} &= Z_i A_{im}^T + A_{im} Z_i + \varepsilon_{1i} \rho_i^2 I + (\varepsilon_{2i} + \varepsilon_{3i} \rho_i^2) H_{im} H_{im}^T + \sum_{j=1, j \neq i}^S C_{jim} C_{jim}^T + \sum_{j=1, j \neq i}^S Y_{jim} Y_{jim}^T, \\
 \overline{TZ}_{i,m} &= \overbrace{[T_{i1m} Z_i \quad T_{i2m} Z_i \quad \cdots \quad T_{ii-1m} Z_i \quad T_{ii+1m} Z_i \quad \cdots \quad T_{iSm} Z_i]^T}^{S-1}, \quad \overline{NZ}_{i,mn} = \begin{bmatrix} N_{im} Z_i \\ N_{in} Z_i \end{bmatrix},
 \end{aligned}$$

$$\overline{BG}_{i,mm} = \begin{bmatrix} B_{im}G_{im} \\ B_{in}G_{im} \end{bmatrix}, \overline{E_1Z}_{i,mm} = \begin{bmatrix} E_{i1m}Z_i \\ E_{i1n}Z_i \end{bmatrix}, \overline{E_2Z}_{i,mm} = \begin{bmatrix} E_{i2m}Z_i \\ E_{i2n}Z_i \end{bmatrix}, \overline{E_3G}_{i,mm} = \begin{bmatrix} E_{i3m}G_{im} \\ E_{i3n}G_{im} \end{bmatrix},$$

$$\overline{\overline{TZ}}_{i,mm} = \overbrace{[T_{i1m}Z_i \ T_{i1n}Z_i \ \dots \ T_{ii-1m}Z_i \ T_{ii-1n}Z_i \ T_{ii+1m}Z_i \ T_{ii+1n}Z_i \ \dots \ T_{iSm}Z_i \ T_{iSn}Z_i]^T}^{2(S-1)},$$

$$\varphi_{33} = \varphi_{44} = \text{diag}\{\varepsilon_{ii}I, \varepsilon_{ii}I\}, \varphi_{55} = \text{diag}\{\varepsilon_{2i}I, \varepsilon_{2i}I\}, \varphi_{66} = \varphi_{77} = \text{diag}\{\varepsilon_{3i}I, \varepsilon_{3i}I\}.$$

Proof: letting $P_i = Z_i^{-1}$ and noting $G_{im} = K_{im}Z$.

Then, pre-multiplying and post-multiplying $\text{diag}\{P_i, I, I, \dots, I, I\}$ to (13) results in

$$\begin{bmatrix} P_i\varphi_{i,m}P_i & * & * & * & * & * & * & * \\ I & -\frac{I}{S-1} & * & * & * & * & * & * \\ N_{im} & 0 & -\varepsilon_{1i}I & * & * & * & * & * \\ B_{im}K_{im} & 0 & 0 & -\varepsilon_{1i}I & * & * & * & * \\ E_{i1m} & 0 & 0 & 0 & -\varepsilon_{2i}I & * & * & * \\ E_{i2m} & 0 & 0 & 0 & 0 & -\varepsilon_{3i}I & * & * \\ E_{i3m}K_{im} & 0 & 0 & 0 & 0 & 0 & -\varepsilon_{3i}I & * \\ \overline{T}_{i,m} & 0 & 0 & 0 & 0 & 0 & 0 & -I \end{bmatrix} < 0, \quad (15)$$

$$i = 1, 2, \dots, S; \quad m = 1, 2, \dots, r_i,$$

where $\overline{T}_{i,m} = \overbrace{[T_{i1m} \ T_{i2m} \ \dots \ T_{ii-1m} \ T_{ii+1m} \ \dots \ T_{iSm}]^T}^{S-1}$.

Applying the Schur complement to (15) results in the condition (6). It is similar to prove that the (14) is equivalent to the condition (7). Therefore, it follows from Theorem 1 that the interconnected system (5) is robustly stable. Thus, the proof is completed.

4. Simulation Examples

In this section, two simulation examples are presented to illustrate the fuzzy controller design method developed in this paper.

Example 1: Consider a nonlinear interconnected system composed of two subsystems which are described as follows

Subsystem 1:

$$\begin{aligned} \dot{x}_{11}(t) &= 0.2\sin(t)x_{11}(t) - 1.5x_{12}(t) + 0.1x_{11}(t)x_{12}(t) + u_1(t)(1 - x_{11}(t)) \\ &\quad + 0.1\sin(t)x_{11}(t) - 0.3x_{21}(t) + 0.2x_{22}(t) - 0.1x_{22}^3(t); \\ \dot{x}_{12}(t) &= x_{11}(t) - (3 + 0.2\cos t)x_{12}(t) + (1 - 0.2\cos t - x_{12}(t))u_1(t) \\ &\quad + 0.1x_{21}(t) - 0.4x_{22}(t) - 0.1x_{22}^3(t); \end{aligned} \quad (16)$$

Subsystem 2:

$$\begin{aligned} \dot{x}_{21}(t) &= 0.4\sin(t)x_{21}(t) + x_{21}(t) - 0.2x_{11}(t)x_{12}(t) + u_2(t)(1 - 2x_{21}(t)) \\ &\quad + 0.2\sin(t)x_{21}(t) - 0.3x_{11}(t) + 0.2x_{12}(t) - 0.1x_{12}^3(t); \\ \dot{x}_{22}(t) &= -x_{21}(t) + (1 - 0.1\cos t)x_{12}(t) + (0.1\cos(t)x_{22}(t) - 0.2\cos t \\ &\quad - x_{22}(t))u_2(t) - 0.1x_{11}(t) - 0.8x_{12}(t) - 0.7x_{12}^3(t). \end{aligned}$$

Then, we establish the T-S fuzzy bilinear model for each interconnected subsystem. Thus, the nonlinear subsystem (16) are approximated by the following fuzzy models

Subsystem 1:

$$\begin{aligned}
 R_1^1: & \text{ if } x_{11} \text{ is } F_{11}^1 \\
 & \text{ then } \dot{x}_1(t) = (A_{11} + \Delta A_{11})x_1(t) + (N_{11} + \Delta N_{11})x_1(t)u_1(t) + (B_{11} + \Delta B_{11})u_1(t) \\
 & \quad + (C_{211} + \Delta C_{211})x_2(t); \\
 R_1^2: & \text{ if } x_{11} \text{ is } F_{11}^2 \\
 & \text{ then } \dot{x}_1(t) = (A_{12} + \Delta A_{12})x_1(t) + (N_{12} + \Delta N_{12})x_1(t)u_1(t) + (B_{12} + \Delta B_{12})u_1(t) \\
 & \quad + (C_{212} + \Delta C_{212})x_2(t);
 \end{aligned} \tag{17}$$

where

$$\begin{aligned}
 A_{11} &= \begin{bmatrix} 0 & -1 \\ 1 & -3 \end{bmatrix}, A_{12} = \begin{bmatrix} 0 & -2 \\ 1 & -3 \end{bmatrix}; B_{11} = B_{12} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}; N_{11} = N_{12} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}; C_{211} = \begin{bmatrix} -0.3 & 0.2 \\ 0.1 & -0.4 \end{bmatrix}, \\
 C_{212} &= \begin{bmatrix} -0.3 & 0.1 \\ 0.1 & 0.5 \end{bmatrix}; E_{111} = E_{112} = \begin{bmatrix} 0.4 & 0 \\ 0 & 0.1 \end{bmatrix}; E_{121} = E_{122} = \begin{bmatrix} 0.1 & 0 \\ 0 & 0 \end{bmatrix}; E_{131} = E_{132} = \begin{bmatrix} 0 \\ 0.2 \end{bmatrix}; \\
 T_{211} = T_{212} &= \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, H_{11} = H_{12} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; Y_{211} = Y_{212} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}.
 \end{aligned}$$

The membership functions of subsystem 1 are chosen as

$$\mu_{F_{11}^1}(x_{11}) = \begin{cases} 0, & x_{11}(t) < -5 \\ 0.1x_{11} + 0.5, & -5 \leq x_{11}(t) < 5, \\ 1, & x_{11}(t) > 5 \end{cases} \quad \mu_{F_{11}^2}(x_{11}) = 1 - \mu_{F_{11}^1}(x_{11})$$

Subsystem 2:

$$\begin{aligned}
 R_2^1: & \text{ if } x_{21} \text{ is } F_{21}^1 \\
 & \text{ then } \dot{x}_2(t) = (A_{21} + \Delta A_{21})x_2(t) + (N_{21} + \Delta N_{21})x_2(t)u_2(t) + (B_{21} + \Delta B_{21})u_2(t) \\
 & \quad + (C_{121} + \Delta C_{121})x_1(t); \\
 R_2^2: & \text{ if } x_{21} \text{ is } F_{21}^2 \\
 & \text{ then } \dot{x}_2(t) = (A_{22} + \Delta A_{22})x_2(t) + (N_{22} + \Delta N_{22})x_2(t)u_2(t) + (B_{22} + \Delta B_{22})u_2(t) \\
 & \quad + (C_{122} + \Delta C_{122})x_1(t);
 \end{aligned} \tag{18}$$

where

$$\begin{aligned}
 A_{21} &= \begin{bmatrix} 1 & 0 \\ -1 & -1 \end{bmatrix}, A_{22} = \begin{bmatrix} 1 & 0 \\ -1 & 1 \end{bmatrix}; B_{21} = B_{22} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}; N_{21} = N_{22} = \begin{bmatrix} -2 & 0 \\ 0 & 1 \end{bmatrix}; C_{121} = \begin{bmatrix} -0.3 & 0.2 \\ 0.1 & -0.8 \end{bmatrix}; \\
 C_{122} &= \begin{bmatrix} -0.3 & 0.1 \\ 0.1 & -1.5 \end{bmatrix}; E_{211} = E_{212} = \begin{bmatrix} 0.4 & 0 \\ 0 & 0.1 \end{bmatrix}; E_{221} = E_{222} = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.1 \end{bmatrix}; E_{231} = E_{232} = \begin{bmatrix} 0 \\ -0.1 \end{bmatrix}; \\
 T_{121} = T_{122} &= \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}; H_{21} = H_{22} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; Y_{121} = Y_{122} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}.
 \end{aligned}$$

The membership functions of subsystem 2 are chosen as

$$\mu_{F_{21}^1}(x_{21}) = \begin{cases} 0, & x_{21}(t) < -5 \\ 0.1x_{21} + 0.5, & -5 \leq x_{21}(t) < 5, \\ 1, & x_{21}(t) > 5 \end{cases} \quad \mu_{F_{21}^2}(x_{21}) = 1 - \mu_{F_{21}^1}(x_{21})$$

Based on Eqs. (13) and (14), for $\rho_1 = 0.46, \rho_2 = 0.83$ and $\varepsilon_{11} = \varepsilon_{12} = 1.45, \varepsilon_{21} = \varepsilon_{22} = 0.68, \varepsilon_{31} = \varepsilon_{32} = 0.01$, we can thereby obtained the following feasible solution:

$$P_1 = \begin{bmatrix} 12.0440 & 5.1447 \\ 5.1447 & 23.1160 \end{bmatrix}, P_2 = \begin{bmatrix} 4.3347 & 1.0980 \\ 1.0980 & 5.0469 \end{bmatrix},$$

$$K_{11} = [-0.4652 \quad -0.3452], K_{12} = [-0.8562 \quad -0.2867]; K_{21} = [-0.2024 \quad -0.3851]; K_{22} = [-0.3797 \quad -0.3682].$$

Figs. 1 - 3 illustrate the simulation results of applying the robust controller to the fuzzy interconnected system under initial conditions $x_{10} = [1.2 \quad -1.6]^T$ and $x_{20} = [-1.9 \quad 1.2]^T$. It can be seen that with the fuzzy control law (4) the closed-loop system is robustly stable.

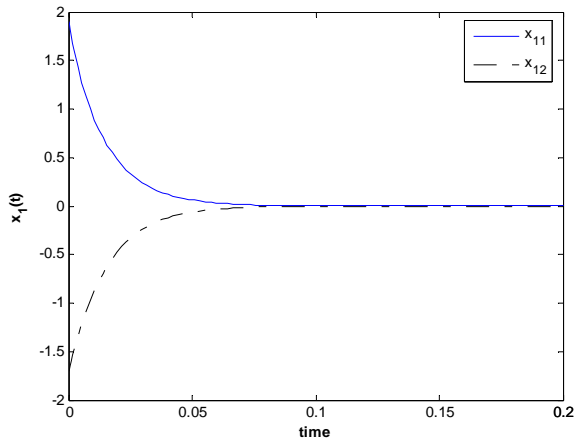


Fig. 1. State responses of subsystem 1.

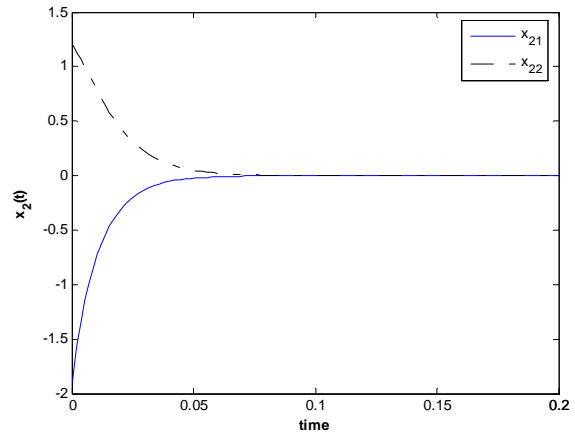


Fig. 2. State responses of subsystem 2.

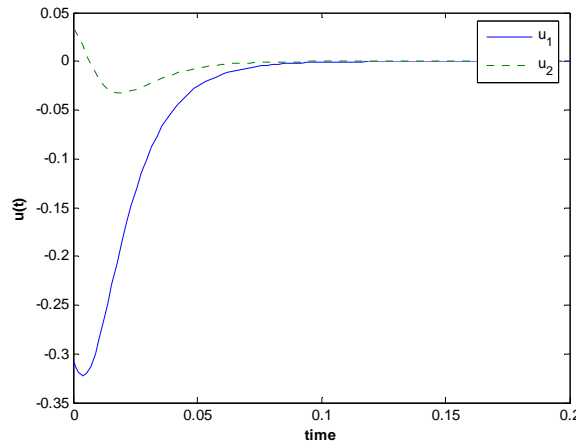


Fig. 3. Control trajectories.

Example 2: Consider the dynamics of an isothermal continuous stirred tank reactor for the Van de Vusse

Subsystem 1:

$$\dot{x}_{11}(t) = -50x_{11}(t) - 100x_{11}^2(t) + u_1(10 - x_{11}(t)) + 10x_{21}(t)$$

$$\dot{x}_{12}(t) = 50x_{11}(t) - 50x_{12}(t) - u_1x_{12}(t) + 20x_{21}(t) + 5x_{22}(t)$$

Subsystem 2:

$$\dot{x}_{21}(t) = 50x_{21}(t) - 50x_{21}^2(t) + u_2(10 + x_{21}(t)) + 8x_{11}(t)$$

$$\dot{x}_{22}(t) = 100x_{22}(t) + u_2(x_{12}(t) + 10) + 5x_{12}(t)$$

(19)

From the system equation (19), some equilibrium points are tabulated in Table 1. According to these equilibrium points, $[x_e \quad u_e]$, which are also chosen as the desired operating points, $[x'_e \quad u'_e]$, we can use the similar modeling method that is described in [8].

Table 1 Data for equilibrium points.

x_{1e}^T	u_{1e}	x_{2e}^T	u_{2e}
[2.3 -4.1616]	40.9756	[2.8 3.4845]	10.7031
[4.5 -3.4770]	139.3103	[4.6 3.6745]	41.3014
[5.4 -2.9495]	188.7013	[5.6 3.9398]	79.5313

Thus, the system (19) can be represented by

Subsystem 1:

R_1^1 : if x_{11} is about 2.3

then $\dot{x}_{1\delta}(t) = A_{11}x_{1\delta}(t) + B_{11}u_{1\delta}(t) + N_{11}x_{1\delta}(t)u_{1\delta}(t) + C_{211}x_{2\delta}(t)$

R_1^2 : if x_{11} is about 4.5

then $\dot{x}_{1\delta}(t) = A_{12}x_{1\delta}(t) + B_{12}u_{1\delta}(t) + N_{12}x_{1\delta}(t)u_{1\delta}(t) + C_{212}x_{2\delta}(t)$

R_1^3 : if x_{11} is about 5.4

then $\dot{x}_{1\delta}(t) = A_{13}x_{1\delta}(t) + B_{13}u_{1\delta}(t) + N_{13}x_{1\delta}(t)u_{1\delta}(t) + C_{213}x_{2\delta}(t)$

(20)

where

$$A_{11} = \begin{bmatrix} -75.2383 & 7.7946 \\ 50 & -100 \end{bmatrix}, A_{12} = \begin{bmatrix} -87.3005 & 11.7315 \\ 50 & -100 \end{bmatrix}, A_{13} = \begin{bmatrix} -98.6262 & 14.8277 \\ 50 & -100 \end{bmatrix},$$

$$N_{11} = N_{12} = N_{13} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}; B_{11} = B_{12} = B_{13} = \begin{bmatrix} 10 \\ 0 \end{bmatrix}; C_{211} = C_{212} = C_{213} = \begin{bmatrix} 10 & 0 \\ 20 & 5 \end{bmatrix};$$

$$x_{1\delta} = x_1(t) - x_{1e}, u_{1\delta} = u_1(t) - u_{1e},$$

Subsystem 2:

R_2^1 : if x_{21} is about 2.8

then $\dot{x}_{2\delta}(t) = A_{21}x_{2\delta}(t) + B_{21}u_{2\delta}(t) + N_{21}x_{2\delta}(t)u_{2\delta}(t) + C_{121}x_{1\delta}(t)$

R_2^2 : if x_{21} is about 4.6

then $\dot{x}_{2\delta}(t) = A_{22}x_{2\delta}(t) + B_{22}u_{2\delta}(t) + N_{22}x_{2\delta}(t)u_{2\delta}(t) + C_{122}x_{1\delta}(t)$

R_2^3 : if x_{21} is about 5.6

then $\dot{x}_{2\delta}(t) = A_{23}x_{2\delta}(t) + B_{23}u_{2\delta}(t) + N_{23}x_{2\delta}(t)u_{2\delta}(t) + C_{123}x_{1\delta}(t)$

(21)

where

$$A_{21} = \begin{bmatrix} -55.5332 & 11.3308 \\ 50 & -50 \end{bmatrix}, A_{22} = \begin{bmatrix} -45.8303 & 9.7505 \\ 50 & -50 \end{bmatrix}, A_{23} = \begin{bmatrix} -37.7909 & 8.9544 \\ 50 & -50 \end{bmatrix};$$

$$N_{21} = N_{22} = N_{23} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}; B_{21} = B_{22} = B_{23} = \begin{bmatrix} 10 \\ 0 \end{bmatrix}; C_{121} = C_{122} = C_{123} = \begin{bmatrix} 10 & 0 \\ 20 & 5 \end{bmatrix};$$

$$x_{2\delta} = x_2(t) - x_{2e}, u_{2\delta} = u_2(t) - u_{2e}.$$

Now, we want to consider the fuzzy system with uncertainties, where the system parameters are randomly varied within 50 % of their nominal values. Based on the Assumption 1, we can define the matrices and as follows:

$$E_{111} = E_{112} = E_{113} = \begin{bmatrix} 50 & 100 \\ 0 & 50 \end{bmatrix}; E_{121} = E_{122} = E_{123} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}; E_{131} = E_{132} = E_{133} = \begin{bmatrix} 0 \\ 1 \end{bmatrix};$$

$$T_{211} = T_{212} = T_{213} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}; H_{11} = H_{12} = H_{13} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; Y_{211} = Y_{212} = Y_{213} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix};$$

$$E_{211} = E_{212} = E_{213} = \begin{bmatrix} 50 & 50 \\ 0 & 50 \end{bmatrix}; E_{221} = E_{222} = E_{223} = \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}; E_{231} = E_{232} = E_{233} = \begin{bmatrix} 0 \\ -1 \end{bmatrix};$$

$$T_{121} = T_{122} = T_{123} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}; H_{21} = H_{22} = H_{23} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; Y_{121} = Y_{122} = Y_{123} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

The membership functions of two subsystems are illustrated in Fig. 4 and Fig. 5, respectively.

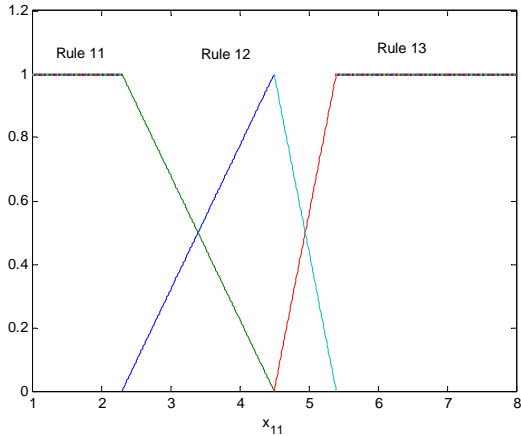


Fig. 4. Membership functions of subsystem 1.

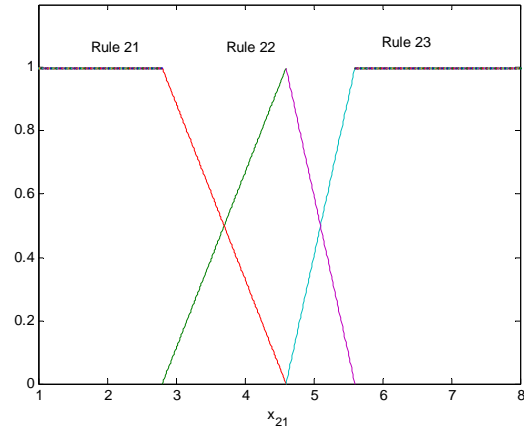


Fig. 5. Membership functions of subsystem 2.

By applying Theorem 2 with for $\rho = 0.45, \lambda = 1.02$, $\varepsilon_{11} = \varepsilon_{12} = \varepsilon_{13} = 0.9, \varepsilon_{21} = \varepsilon_{22} = \varepsilon_{23} = 0.3$, $\varepsilon_{31} = \varepsilon_{32} = \varepsilon_{33} = 1.4$ and solving the corresponding LMIs, we can obtain the following feasible solution:

$$P_1 = \begin{bmatrix} 4.2727 & -1.3007 \\ -1.3007 & 6.4906 \end{bmatrix}, P_2 = \begin{bmatrix} 14.1872 & -1.9381 \\ -1.9381 & 13.0104 \end{bmatrix};$$

$$K_{11} = [-0.4233 \quad -0.5031], K_{12} = [-0.5961 \quad -0.7049], K_{13} = [-1.0372 \quad 0.2120];$$

$$K_{21} = [-0.4593 \quad -0.3874], K_{22} = [-0.4121 \quad -0.4113], K_{23} = [-0.6371 \quad -0.5911].$$

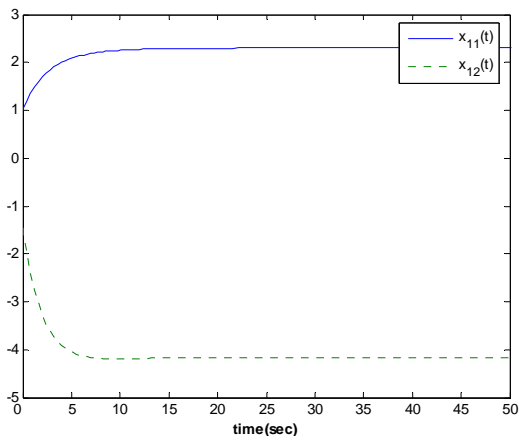


Fig. 6. State responses of Subsystem 1.

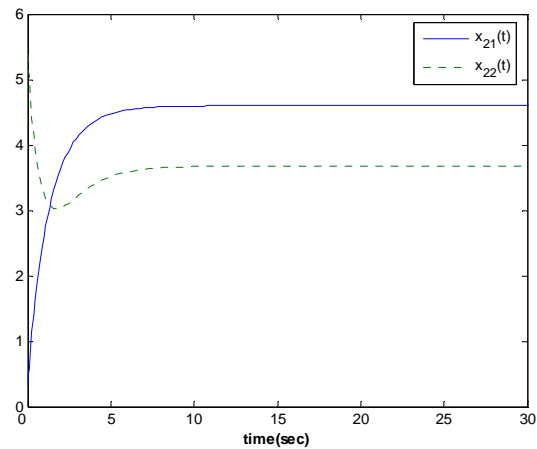


Fig. 7. State responses of Subsystem 2.

The simulation results of applying the fuzzy control (4) to the systems (20)-(21) with $x'_{1e} = [2.3 \quad -4.1616]^T, u'_{1e} = 40.9756$ and $x'_{2e} = [4.6 \quad 3.6745]^T, u'_{2e} = 41.3014$, under initial conditions

$[1.2 \ -1.5]^T$ and $[0.5 \ 3.2]^T$ are shown in Fig. 6 and Fig. 7, respectively. One can find that all the states of subsystem 1 approach to the equilibrium state $[2.3 \ -4.1616]^T$ after 10 s and the states of subsystem 2 approach to the equilibrium state $[4.6 \ 3.6745]^T$ after 12 s. These simulation results verify that the proposed decentralized fuzzy controller (4) can render the robust stability of the closed-loop systems.

5. Conclusions

In this paper, a T-S fuzzy bilinear model is proposed to study the robust control problems for nonlinear interconnected systems using fuzzy decentralized control. Based on the Lyapunov criterion, the sufficient conditions for robust stabilization of the interconnected system are presented. The decentralized controllers designing problems can be formulated as a convex optimization problem with LMI constraints. The simulation examples are included to show the effectiveness of the proposed approach. The delay-dependent control and robust non-fragile control based on bilinear model will further investigate in the future work.

References

- [1]. K. Yuan, H. X. Li and J. Cao, Robust stabilization of the distributed parameter system with time delay via fuzzy control, *IEEE Trans. Fuzzy Systems*, Vol. 16, Issue 3, 2008, pp. 567-584.
- [2]. S. S. Zhou, J. Lam and W. X. Zheng, Control design for fuzzy systems based on relaxed non-quadratic stability and H-infinite performance conditions, *IEEE Trans. Fuzzy Systems*, Vol. 15, Issue 2, 2007, pp. 188-198.
- [3]. W. J. Wang and W. W. Lin, Decentralized PDC for large-scale T-S fuzzy systems, *IEEE Trans. Fuzzy Systems*, Vol. 13, Issue 6, 2005, pp. 779-786.
- [4]. R. J. Wang, Nonlinear decentralized state feedback controller for uncertain fuzzy time-delay interconnected systems, *Fuzzy Sets and Systems*, Vol. 151, Issue 1, 2005, pp. 191-204.
- [5]. Y. Liu, S. W. Zhao and J. Q. Lu, New Results on H-infinite Filter Design for Nonlinear Systems With Time Delay via T-S Fuzzy Models, *IEEE Trans. Fuzzy Systems*, Vol. 19, Issue 1, 2011, pp. 93-199.
- [6]. H. Yousef, M. Hamdy and E. El-Madbouly, Robust adaptive fuzzy semi-decentralized control for a class of large-scale nonlinear systems using input-output linearization concept, *Int. J. Robust Nonlinear Control*, Vol. 20, Issue 1, 2010, pp. 27-40.
- [7]. D. L. Elliott, Bilinear systems in Encyclopedia of Electrical Engineering, Wiley, New York, 1999.
- [8]. T. H. S. Li and S. H. Tsai, T-S fuzzy bilinear model and fuzzy controller design for a class of nonlinear systems, *IEEE Trans. Fuzzy Systems*, Vol. 15, Issue 3, 2007, pp. 494-505.
- [9]. S. H. Tsai and T. H. S. Li, Robust fuzzy control of a class fuzzy bilinear systems with time-delay, *Chaos, Solitons and Fractals*, Vol. 39, 2009, pp. 2028-2040.
- [10]. T. H. S. Li and S. H. Tsai, et al. Robust H_∞ fuzzy control for a class of uncertain discrete fuzzy bilinear systems, *IEEE Trans. Systems, Man, and Cybernetics*, Vol. 38, Issue 2, 2008, pp. 510-526.
- [11]. J. M. Li, G. Zhang and C. X. Du, Robust H-infinite control for a class of multiple input fuzzy bilinear systems with uncertainties, *Control Theory and Applications*, Vol. 26, Issue 9, 2009, pp. 1298-1302.
- [12]. G. Zhang and J. M. L, Non-Fragile Guaranteed Cost Control of discrete-time Fuzzy Bilinear System, *Journal of Systems Engineering and Electronics*, Vol. 21, Issue 4, 2010, pp. 629-634 .
- [13]. J. M. Lin and G. Zhang, Non-Fragile Guaranteed Cost Control of T-S Fuzzy Time-varying Delay Systems with Local Bilinear Models, *Iranian Journal of Fuzzy Systems*, Vol. 9, Issue 2, 2012, pp. 45-64.
- [14]. R. J. Wang, W. W. Lin and W. J. Wang, Stabilizability of linear quadratic state feedback for uncertain fuzzy time-delay systems, *IEEE Trans. Systems, Man, and Cybernetics*, Vol. 34, Issue 2, 2004, pp. 1288-1292.
- [15]. X. Li and C. E. de Souza, Delayed-dependent robust stability and stabilization of uncertain linear delay systems: a linear matrix inequality approach, *IEEE Trans. Automatic Control*, Vol. 42, Issue 8, 1997, pp. 1144-1148.

Digital Sensors and Sensor Systems: Practical Design

Sergey Y. Yurish



Formats: printable pdf (Acrobat) and print (hardcover), 419 pages

ISBN: 978-84-616-0652-8,
e-ISBN: 978-84-615-6957-1

The goal of this book is to help the practitioners achieve the best metrological and technical performances of digital sensors and sensor systems at low cost, and significantly to reduce time-to-market. It should be also useful for students, lectures and professors to provide a solid background of the novel concepts and design approach.

Book features include:

- Each of chapter can be used independently and contains its own detailed list of references
- Easy-to-repeat experiments
- Practical orientation
- Dozens examples of various complete sensors and sensor systems for physical and chemical, electrical and non-electrical values
- Detailed description of technology driven and coming alternative to the ADC a frequency (time)-to-digital conversion

Digital Sensors and Sensor Systems: Practical Design will greatly benefit undergraduate and at PhD students, engineers, scientists and researchers in both industry and academia. It is especially suited as a reference guide for practitioners, working for Original Equipment Manufacturers (OEM) electronics market (electronics/hardware), sensor industry, and using commercial-off-the-shelf components

http://sensorsportal.com/HTML/BOOKSTORE/Digital_Sensors.htm



Handbook of Laboratory Measurements and Instrumentation

Maria Teresa Restivo
Fernando Gomes de Almeida
Maria de Fátima Chouzal
Joaquim Gabriel Mendes
António Mendes Lopes

The Handbook of Laboratory Measurements and Instrumentation presents experimental and laboratory activities with an approach as close as possible to reality, even offering remote access to experiments, providing to the reader an excellent tool for learning laboratory techniques and methodologies. Book includes dozens videos, animations and simulations following each of chapters. It makes the title very valued and different from existing books on measurements and instrumentation.

Order online:

http://www.sensorsportal.com/HTML/BOOKSTORE/Handbook_of_Measurements.htm

Aims and Scope

Sensors & Transducers is a peer reviewed international, interdisciplinary journal that provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes original research articles, timely state-of-the-art reviews and application specific articles with the following devices areas:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing and interfacing;
- Frequency (period, duty-cycle)-to-code converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Further information on this journal is available from the Publisher's web site:
<http://www.sensorsportal.com/HTML/DIGEST/Submission.htm>

Subscriptions

An annual subscription includes 12 regular issues and some special issues. Annual subscription rates for 2013 are the following:

Electronic version (in printable pdf format): 400.00 EUR

Printed with b/w illustrations: 640.00 EUR

Printed full color version: 760.00 EUR

40 % discount is available for IFSA Members.

Prices include shipping costs by mail. Further information about subscription is available through IFSA Publishing's web site: http://www.sensorsportal.com/HTML/DIGEST/Journal_Subscription.htm

Advertising Information

If you are interested in advertising or other commercial opportunities please e-mail sales@sensorsportal.com and your enquiry will be passed to the correct person who will respond to you within 24 hours. Please download also our Media Planner 2013: http://www.sensorsportal.com/DOWNLOADS/Media_Planner_2013.pdf

Books for Review

Publications should be sent to the IFSA Publishing Office: Ronda de Ramon Otero Pedrayo, 42C, 1-5, 08860, Castelldefels, Barcelona, Spain.

Abstracting Services

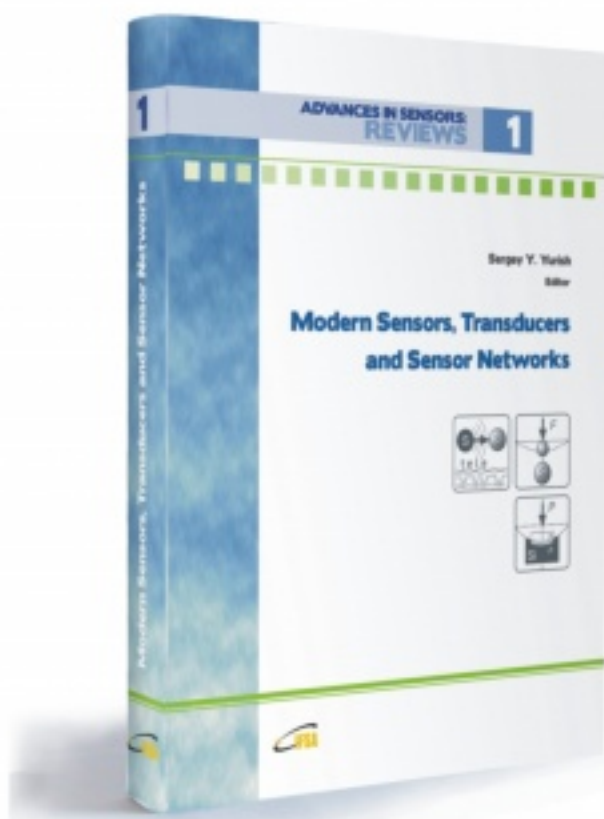
This journal is cited, indexed and abstracted by Chemical Abstracts, EBSCO Publishing, IndexCopernicus Journals Master List, ProQuest Science Journals, CAS Source Index (CASSI), Ulrich's Periodicals Directory, Scirus, Google Scholar, etc. Since 2011 *Sensors & Transducers* journal is covered and indexed by EI Compendex index (including a Scopus, Embase, Engineering Village and Reaxys) in *Elsevier* products.

Instructions for Authors

Please visit the journal web page <http://www.sensorsportal.com/HTML/DIGEST/Submission.htm> Authors must follow the instructions very carefully when submitting their manuscripts. Manuscript must be send electronically in both: MS Word 2003 for Windows (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com

Sergey Y. Yurish
Editor

Modern Sensors, Transducers and Sensor Networks



Modern Sensors, Transducers and Sensor Networks is the first book from the Advances in Sensors: Reviews book Series contains dozen collected sensor related state-of-the-art reviews written by 31 internationally recognized experts from academia and industry.

Built upon the series Advances in Sensors: Reviews - a premier sensor review source, the *Modern Sensors, Transducers and Sensor Networks* presents an overview of highlights in the field. Coverage includes current developments in sensing nanomaterials, technologies, MEMS sensor design, synthesis, modeling and applications of sensors, transducers and wireless sensor networks, signal detection and advanced signal processing, as well as new sensing principles and methods of measurements.

Modern Sensors, Transducers and Sensor Networks is intended for anyone who wants to cover a comprehensive range of topics in the field of sensors paradigms and developments. It provides guidance for technology solution developers from academia, research institutions, and industry, providing them with a broader perspective of sensor science and industry.

Order online:

http://sensorsportal.com/HTML/BOOKSTORE/Advance_in_Sensors.htm



www.sensorsportal.com