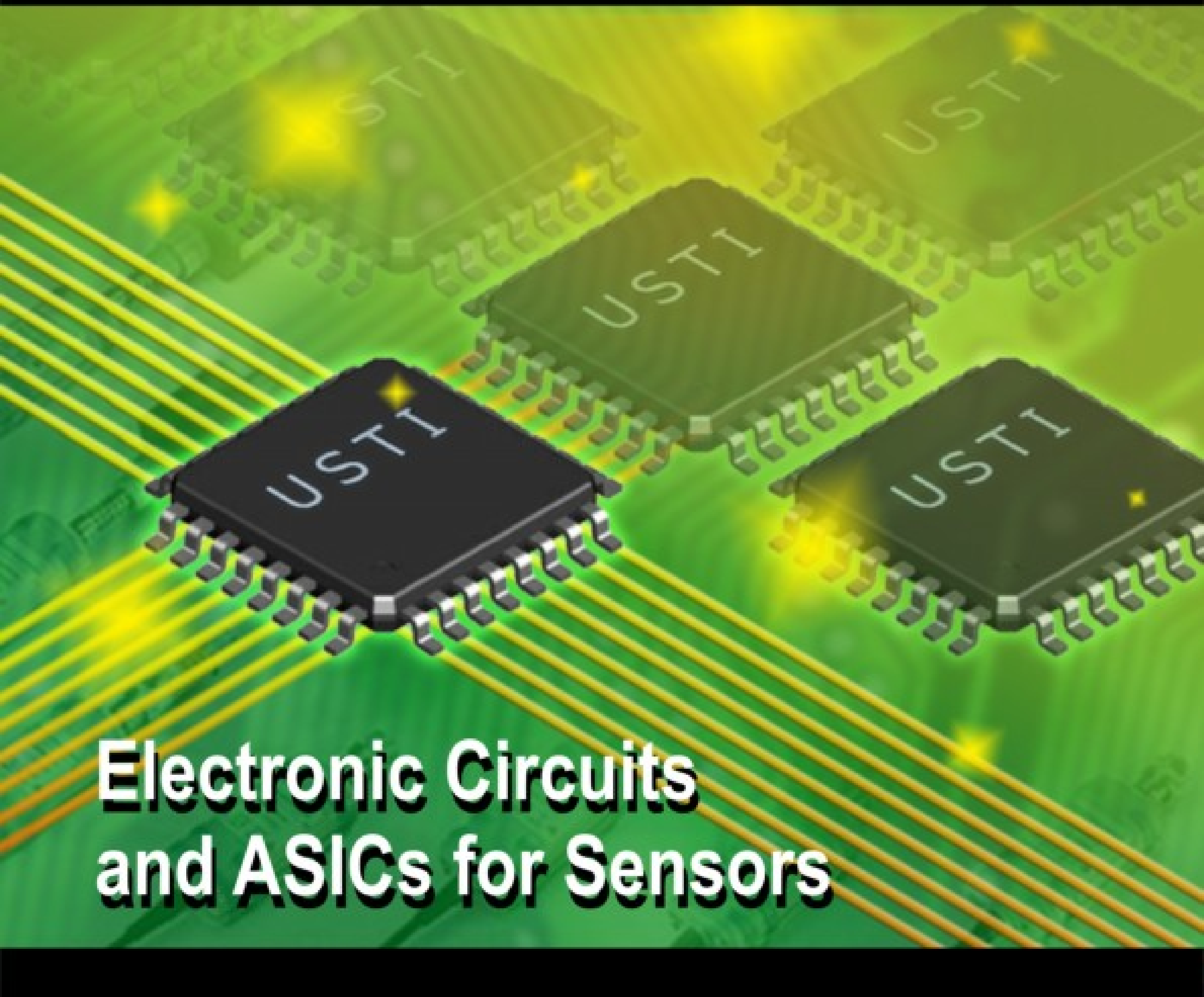
ISSN 1726-5479

SENSORS & TRANSDUCERS

vol. 93
6/08



Electronic Circuits and ASICs for Sensors

International Frequency Sensor Association Publishing
IFSA

Sensors & Transducers

Volume 93
Issue 6
June 2008

www.sensorsportal.com

ISSN 1726-5479

Editor-in-Chief: professor Sergey Y. Yurish, phone: +34 696067716, fax: +34 93 4011989,
e-mail: editor@sensorsportal.com

Editors for Western Europe
Meijer, Gerard C.M., Delft University of Technology, The Netherlands
Ferrari, Vittorio, Universitá di Brescia, Italy

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

Editor South America
Costa-Felix, Rodrigo, Inmetro, Brazil

Editor for Eastern Europe
Sachenko, Anatoly, Ternopil State Economic University, Ukraine

Editor for Asia
Ohyama, Shinji, Tokyo Institute of Technology, Japan

Editorial Advisory Board

Abdul Rahim, Ruzairi, Universiti Teknologi, Malaysia
Ahmad, Mohd Noor, Nothern University of Engineering, Malaysia
Annamalai, Karthigeyan, National Institute of Advanced Industrial Science and Technology, Japan
Arcega, Francisco, University of Zaragoza, Spain
Arguel, Philippe, CNRS, France
Ahn, Jae-Pyoung, Korea Institute of Science and Technology, Korea
Arndt, Michael, Robert Bosch GmbH, Germany
Ascoli, Giorgio, George Mason University, USA
Atalay, Selcuk, Inonu University, Turkey
Atghiaee, Ahmad, University of Tehran, Iran
Augutis, Vygantas, Kaunas University of Technology, Lithuania
Avachit, Patil Lalchand, North Maharashtra University, India
Ayesh, Aladdin, De Montfort University, UK
Bahreyni, Behraad, University of Manitoba, Canada
Baoxian, Ye, Zhengzhou University, China
Barford, Lee, Agilent Laboratories, USA
Barlingay, Ravindra, RF Arrays Systems, India
Basu, Sukumar, Jadavpur University, India
Beck, Stephen, University of Sheffield, UK
Ben Bouzid, Sihem, Institut National de Recherche Scientifique, Tunisia
Binnie, T. David, Napier University, UK
Bischoff, Gerlinde, Inst. Analytical Chemistry, Germany
Bodas, Dhananjay, IMTEK, Germany
Borges Carval, Nuno, Universidade de Aveiro, Portugal
Bousbia-Salah, Mounir, University of Annaba, Algeria
Bouvet, Marcel, CNRS – UPMC, France
Brudzewski, Kazimierz, Warsaw University of Technology, Poland
Cai, Chenxin, Nanjing Normal University, China
Cai, Qingyun, Hunan University, China
Campanella, Luigi, University La Sapienza, Italy
Carvalho, Vitor, Minho University, Portugal
Cecelja, Franjo, Brunel University, London, UK
Cerda Belmonte, Judith, Imperial College London, UK
Chakrabarty, Chandan Kumar, Universiti Tenaga Nasional, Malaysia
Chakravorty, Dipankar, Association for the Cultivation of Science, India
Changhai, Ru, Harbin Engineering University, China
Chaudhari, Gajanan, Shri Shivaji Science College, India
Chen, Jiming, Zhejiang University, China
Chen, Rongshun, National Tsing Hua University, Taiwan
Cheng, Kuo-Sheng, National Cheng Kung University, Taiwan
Chiriac, Horia, National Institute of Research and Development, Romania
Chowdhuri, Arijit, University of Delhi, India
Chung, Wen-Yaw, Chung Yuan Christian University, Taiwan
Corres, Jesus, Universidad Publica de Navarra, Spain
Cortes, Camilo A., Universidad Nacional de Colombia, Colombia
Courtois, Christian, Universite de Valenciennes, France
Cusano, Andrea, University of Sannio, Italy
D'Amico, Arnaldo, Università di Tor Vergata, Italy
De Stefano, Luca, Institute for Microelectronics and Microsystem, Italy
Deshmukh, Kiran, Shri Shivaji Mahavidyalaya, Barshi, India
Dickert, Franz L., Vienna University, Austria
Dieguez, Angel, University of Barcelona, Spain
Dimitropoulos, Panos, University of Thessaly, Greece
Ding Jian, Ning, Jiangsu University, China
Djordjevich, Alexandar, City University of Hong Kong, Hong Kong
Donato, Nicola, University of Messina, Italy
Donato, Patricio, Universidad de Mar del Plata, Argentina
Dong, Feng, Tianjin University, China
Drljaca, Predrag, Instersema Sensoric SA, Switzerland
Dubey, Venketesh, Bournemouth University, UK
Enderle, Stefan, University of Ulm and KTB Mechatronics GmbH, Germany
Erdem, Gursan K. Arzum, Ege University, Turkey
Erkmen, Aydan M., Middle East Technical University, Turkey
Estelle, Patrice, Insa Rennes, France
Estrada, Horacio, University of North Carolina, USA
Faiz, Adil, INSA Lyon, France
Fericean, Sorin, Balluff GmbH, Germany
Fernandes, Joana M., University of Porto, Portugal
Francioso, Luca, CNR-IMM Institute for Microelectronics and Microsystems, Italy
Francis, Laurent, University Catholique de Louvain, Belgium
Fu, Weiling, South-Western Hospital, Chongqing, China
Gaura, Elena, Coventry University, UK
Geng, Yanfeng, China University of Petroleum, China
Gole, James, Georgia Institute of Technology, USA
Gong, Hao, National University of Singapore, Singapore
Gonzalez de la Rosa, Juan Jose, University of Cadiz, Spain
Granel, Annette, Goteborg University, Sweden
Graff, Mason, The University of Texas at Arlington, USA
Guan, Shan, Eastman Kodak, USA
Guillet, Bruno, University of Caen, France
Guo, Zhen, New Jersey Institute of Technology, USA
Gupta, Narendra Kumar, Napier University, UK
Hadjiloucas, Sillas, The University of Reading, UK
Hashsham, Syed, Michigan State University, USA
Hernandez, Alvaro, University of Alcala, Spain
Hernandez, Wilmar, Universidad Politecnica de Madrid, Spain
Homentcovschi, Dorel, SUNY Binghamton, USA
Horstman, Tom, U.S. Automation Group, LLC, USA
Hsiai, Tzung (John), University of Southern California, USA
Huang, Jeng-Sheng, Chung Yuan Christian University, Taiwan
Huang, Star, National Tsing Hua University, Taiwan
Huang, Wei, PSG Design Center, USA
Hui, David, University of New Orleans, USA
Jaffrezic-Renault, Nicole, Ecole Centrale de Lyon, France
Jaime Calvo-Galleg, Jaime, Universidad de Salamanca, Spain
James, Daniel, Griffith University, Australia
Janting, Jakob, DELTA Danish Electronics, Denmark
Jiang, Liudi, University of Southampton, UK
Jiao, Zheng, Shanghai University, China
John, Joachim, IMEC, Belgium
Kalach, Andrew, Voronezh Institute of Ministry of Interior, Russia
Kang, Moonho, Sunmoon University, Korea South
Kaniusas, Eugenijus, Vienna University of Technology, Austria
Katake, Anup, Texas A&M University, USA
Kausel, Wilfried, University of Music, Vienna, Austria
Kavasoglu, Nese, Mugla University, Turkey
Ke, Cathy, Tyndall National Institute, Ireland
Khan, Asif, Aligarh Muslim University, Aligarh, India
Kim, Min Young, Koh Young Technology, Inc., Korea South

Ko, Sang Choon, Electronics and Telecommunications Research Institute, Korea South
Kockar, Hakan, Balikesir University, Turkey
Kotulska, Malgorzata, Wroclaw University of Technology, Poland
Kratz, Henrik, Uppsala University, Sweden
Kumar, Arun, University of South Florida, USA
Kumar, Subodh, National Physical Laboratory, India
Kung, Chih-Hsien, Chang-Jung Christian University, Taiwan
Lacnjevac, Caslav, University of Belgrade, Serbia
Lay-Ekuakille, Aime, University of Lecce, Italy
Lee, Jang Myung, Pusan National University, Korea South
Lee, Jun Su, Amkor Technology, Inc. South Korea
Lei, Hua, National Starch and Chemical Company, USA
Li, Genxi, Nanjing University, China
Li, Hui, Shanghai Jiaotong University, China
Li, Xian-Fang, Central South University, China
Liang, Yuanchang, University of Washington, USA
Liawruangrath, Saisunee, Chiang Mai University, Thailand
Liew, Kim Meow, City University of Hong Kong, Hong Kong
Lin, Hermann, National Kaohsiung University, Taiwan
Lin, Paul, Cleveland State University, USA
Linderholm, Pontus, EPFL - Microsystems Laboratory, Switzerland
Liu, Aihua, University of Oklahoma, USA
Liu Changgeng, Louisiana State University, USA
Liu, Cheng-Hsien, National Tsing Hua University, Taiwan
Liu, Songqin, Southeast University, China
Lodeiro, Carlos, Universidade NOVA de Lisboa, Portugal
Lorenzo, Maria Encarnacio, Universidad Autonoma de Madrid, Spain
Lukaszewicz, Jerzy Pawel, Nicholas Copernicus University, Poland
Ma, Zhanfang, Northeast Normal University, China
Majstorovic, Vidosav, University of Belgrade, Serbia
Marquez, Alfredo, Centro de Investigacion en Materiales Avanzados, Mexico
Matay, Ladislav, Slovak Academy of Sciences, Slovakia
Mathur, Prafull, National Physical Laboratory, India
Maurya, D.K., Institute of Materials Research and Engineering, Singapore
Mekid, Samir, University of Manchester, UK
Melnyk, Ivan, Photon Control Inc., Canada
Mendes, Paulo, University of Minho, Portugal
Mennell, Julie, Northumbria University, UK
Mi, Bin, Boston Scientific Corporation, USA
Minas, Graca, University of Minho, Portugal
Moghavvemi, Mahmoud, University of Malaya, Malaysia
Mohammadi, Mohammad-Reza, University of Cambridge, UK
Molina Flores, Esteban, Benemérita Universidad Autónoma de Puebla, Mexico
Moradi, Majid, University of Kerman, Iran
Morello, Rosario, DIMET, University "Mediterranea" of Reggio Calabria, Italy
Mounir, Ben Ali, University of Sousse, Tunisia
Mukhopadhyay, Subhas, Massey University, New Zealand
Neelamegam, Periasamy, Sastra Deemed University, India
Neshkova, Milka, Bulgarian Academy of Sciences, Bulgaria
Oberhammer, Joachim, Royal Institute of Technology, Sweden
Ould Lahoucin, University of Guelma, Algeria
Pamidighanta, Sayanu, Bharat Electronics Limited (BEL), India
Pan, Jisheng, Institute of Materials Research & Engineering, Singapore
Park, Joon-Shik, Korea Electronics Technology Institute, Korea South
Penza, Michele, ENEA C.R., Italy
Pereira, Jose Miguel, Instituto Politecnico de Setebal, Portugal
Petsev, Dimiter, University of New Mexico, USA
Pogacnik, Lea, University of Ljubljana, Slovenia
Post, Michael, National Research Council, Canada
Prance, Robert, University of Sussex, UK
Prasad, Ambika, Gulbarga University, India
Prateepasen, Asa, Kingmoungut's University of Technology, Thailand
Pullini, Daniele, Centro Ricerche FIAT, Italy
Pumera, Martin, National Institute for Materials Science, Japan
Radhakrishnan, S. National Chemical Laboratory, Pune, India
Rajanna, K., Indian Institute of Science, India
Ramadan, Qasem, Institute of Microelectronics, Singapore
Rao, Basuthkar, Tata Inst. of Fundamental Research, India
Raoof, Kosai, Joseph Fourier University of Grenoble, France
Reig, Candid, University of Valencia, Spain
Restivo, Maria Teresa, University of Porto, Portugal
Robert, Michel, University Henri Poincare, France
Rezazadeh, Ghader, Urmia University, Iran
Royo, Santiago, Universitat Politecnica de Catalunya, Spain
Rodriguez, Angel, Universidad Politecnica de Cataluna, Spain
Rothberg, Steve, Loughborough University, UK
Sadana, Ajit, University of Mississippi, USA
Sadeghian Marnani, Hamed, TU Delft, The Netherlands
Sandacci, Serghei, Sensor Technology Ltd., UK
Sapozhnikova, Ksenia, D.I.Mendeleyev Institute for Metrology, Russia
Saxena, Vibha, Bhbha Atomic Research Centre, Mumbai, India
Schneider, John K., Ultra-Scan Corporation, USA
Seif, Selemani, Alabama A & M University, USA
Seifter, Achim, Los Alamos National Laboratory, USA
Sengupta, Deepak, Advance Bio-Photonics, India
Shearwood, Christopher, Nanyang Technological University, Singapore
Shin, Kyuho, Samsung Advanced Institute of Technology, Korea
Shmaliy, Yuriy, Kharkiv National University of Radio Electronics, Ukraine
Silva Girao, Pedro, Technical University of Lisbon, Portugal
Singh, V. R., National Physical Laboratory, India
Slomovitz, Daniel, UTE, Uruguay
Smith, Martin, Open University, UK
Soleymanpour, Ahmad, Damghan Basic Science University, Iran
Somani, Prakash R., Centre for Materials for Electronics Technol., India
Srinivas, Talabattula, Indian Institute of Science, Bangalore, India
Srivastava, Arvind K., Northwestern University, USA
Stefan-van Staden, Raluca-Ioana, University of Pretoria, South Africa
Sumriddetchka, Sarun, National Electronics and Computer Technology Center, Thailand
Sun, Chengliang, Polytechnic University, Hong-Kong
Sun, Dongming, Jilin University, China
Sun, Junhua, Beijing University of Aeronautics and Astronautics, China
Sun, Zhiqiang, Central South University, China
Suri, C. Raman, Institute of Microbial Technology, India
Sysoev, Victor, Saratov State Technical University, Russia
Szewczyk, Roman, Industrial Research Institute for Automation and Measurement, Poland
Tan, Ooi Kiang, Nanyang Technological University, Singapore,
Tang, Dianping, Southwest University, China
Tang, Jaw-Luen, National Chung Cheng University, Taiwan
Teker, Kasif, Frostburg State University, USA
Thumbavanam Pad, Kartik, Carnegie Mellon University, USA
Tian, Gui Yun, University of Newcastle, UK
Tsiantos, Vassilios, Technological Educational Institute of Kaval, Greece
Tsigara, Anna, National Hellenic Research Foundation, Greece
Twomey, Karen, University College Cork, Ireland
Valente, Antonio, University, Vila Real, - U.T.A.D., Portugal
Vaseashta, Ashok, Marshall University, USA
Vazques, Carmen, Carlos III University in Madrid, Spain
Vieira, Manuela, Instituto Superior de Engenharia de Lisboa, Portugal
Vigna, Benedetto, STMicroelectronics, Italy
Vrba, Radimir, Brno University of Technology, Czech Republic
Wandelt, Barbara, Technical University of Lodz, Poland
Wang, Jiangping, Xi'an Shiyou University, China
Wang, Kedong, Beihang University, China
Wang, Liang, Advanced Micro Devices, USA
Wang, Mi, University of Leeds, UK
Wang, Shinn-Fwu, Ching Yun University, Taiwan
Wang, Wei-Chih, University of Washington, USA
Wang, Wensheng, University of Pennsylvania, USA
Watson, Steven, Center for NanoSpace Technologies Inc., USA
Weiping, Yan, Dalian University of Technology, China
Wells, Stephen, Southern Company Services, USA
Wolkenberg, Andrzej, Institute of Electron Technology, Poland
Woods, R. Clive, Louisiana State University, USA
Wu, DerHo, National Pingtung University of Science and Technology, Taiwan
Wu, Zhaoyang, Hunan University, China
Xiu Tao, Ge, Chuzhou University, China
Xu, Lisheng, The Chinese University of Hong Kong, Hong Kong
Xu, Tao, University of California, Irvine, USA
Yang, Dongfang, National Research Council, Canada
Yang, Wuqiang, The University of Manchester, UK
Ymeti, Aurel, University of Twente, Netherland
Yong Zhao, Northeastern University, China
Yu, Haihu, Wuhan University of Technology, China
Yufera Garcia, Alberto, Seville University, Spain
Zagnoni, Michele, University of Southampton, UK
Zeni, Luigi, Second University of Naples, Italy
Zhong, Haoxiang, Henan Normal University, China
Zhang, Minglong, Shanghai University, China
Zhang, Qintao, University of California at Berkeley, USA
Zhang, Weiping, Shanghai Jiao Tong University, China
Zhang, Wenming, Shanghai Jiao Tong University, China
Zhou, Zhi-Gang, Tsinghua University, China
Zorzano, Luis, Universidad de La Rioja, Spain
Zourob, Mohammed, University of Cambridge, UK

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and CD-ROM. Copyright © 2007 by International Frequency Sensor Association. All rights reserved.

Sensors & Transducers Journal

Contents

Volume 93
Issue 6
June 2008

www.sensorsportal.com

ISSN 1726-5479

Editorial

Research Articles

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/Submition.htm

Sensors & Transducers Journal, Vol. 93, Issue 6, June 2008, pp. 29-36

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Design and Implementation of Output Feedback Control for Piezo Actuated Structure Using Embedded System

R. Maheswari, M. Umapathy, L. R. Karalmarx, D. Ezhilarasi
Department of Instrumentation and Control Engineering,
National Institute of Technology, Tiruchirappalli – 620 015, India
E-mail: icr0601@nitt.edu, umapathy@nitt.edu

Received: 3 May 2008 /Accepted: 24 June 2008 /Published: 30 June 2008

Abstract: This paper presents the design of periodic output feedback control using state feedback gain to control the vibration of piezo actuated cantilever beam. The effectiveness of the controller is evaluated through simulation and experimentally by exciting the structure at resonance. Real time implementation of the controller is done using microcontroller. The closed loop eigen values of the system with periodic output feedback and state feedback are identical. *Copyright © 2008 IFSA.*

Keywords: State feedback, Periodic output feedback, Piezoelectric, Smart structure

1. Introduction

Vibrations can be found virtually everywhere, in vehicles, buildings, or machines, flexible structures. Most vibrations are undesirable because they cause unpleasant noises, unwanted stress in structures, and failure of systems. Within the last two decades, much attention has been focused on active control of structures to suppress their structural vibrations. The use of piezoelectric actuators and sensors has shown promising applications in active vibration control of flexible structures [1-2]. These materials in particular piezoceramics (PZT) are attractive for distributed actuators and sensors because they combine small size, low energy consumption, fast response, high efficiency, excellent sensing and significant actuation capabilities and exhibit favorable bonding characteristics. These advantages have encouraged researchers to establish models for flexible structures (Plate, shell, beam) that incorporate piezoelectric actuators/sensors [3-4]. Distributed piezoelectric materials experimentally have proven to be practical in sensing and controlling the vibrations of flexible structures [5-6]. The state feedback controller needs either the availability of the state vector or an estimator but output feedback requires only measurement of the system output. The periodic output feedback control has been implemented for vibration suppression of smart structure cantilever beam [7-8]. The periodic output feedback gain has computed from state feedback gain and closed loop eigen values are same [9]. In this paper, a periodic output feedback controller is designed from the state feedback controller for vibration suppression of piezo actuated cantilever beam and the effectiveness of the controller is evaluated through simulation and experimentally by exciting the structure at resonance.

2. Experimental Set-up and Its Model

A flexible aluminum beam with clamped end as shown in Fig. 1. is considered in this paper. Two piezo ceramic patches are bonded at a distance of 10 mm from the fixed end of the beam. The patch bonded on the bottom surface acts as a sensor and the one on the top surface acts as an actuator. To apply an excitation input to the structure another piezo ceramic patch is bonded on the top surface at a distance of 387.8 mm from the fixed end. The dimensions and properties of the beam and piezo ceramic patches are given in Table 1.

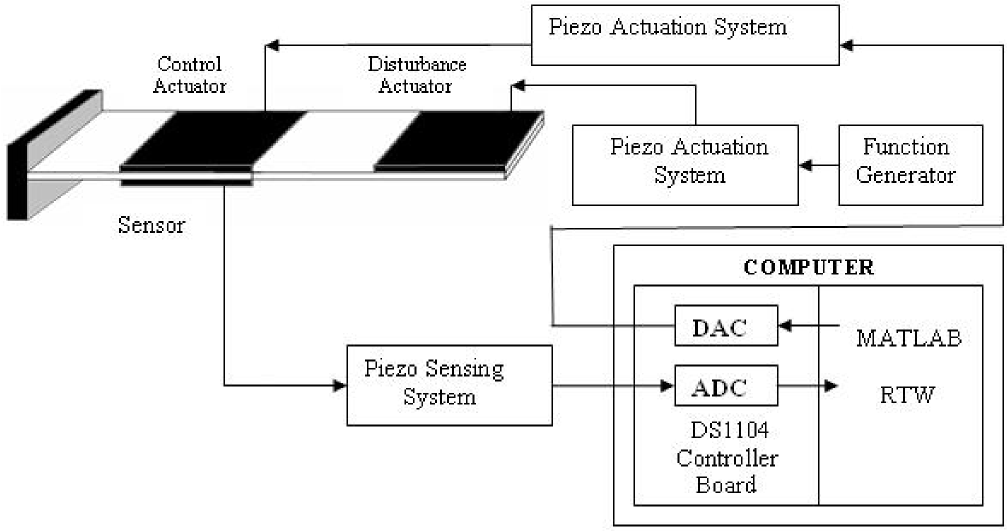


Fig. 1. Schematic diagram of experimental set up.

Table 1. Properties and dimensions of the Aluminium beam and piezoceramic Sensor/Actuator.

Parameter	Aluminium beam	Piezoceramic Sensor/actuator
Length (m)	0.3	0.0765
Width (m)	0.0127	0.0127
Thickness (m)	0.0023	0.005
Young's modulus (Gpa)	71	47.62
Density (kg/m^3)	2700	7500
First natural frequency (Hz)	31.7	----
Piezoelectric strain constant (m V^{-1})	----	$-247\text{x}10^{-12}$
Piezoelectric stress constant (V m N^{-1})	----	$-9\text{x}10^{-3}$

The sensor output is given to the piezo sensing system which consists of charge to voltage converting amplifier. The conditioned piezo sensor signal is given as analog input to dSPACE1104 controller board. The model of a cantilever beam in Fig. 1 is obtained using recursive least square (RLS) method based on ARX model [7]. The excitation signal, input signal and sensor output are given to MATLAB/Simulink through ADC port of dSPACE 1104 system. The RLS algorithm is implemented by writing a C-file S-function used in MATLAB/Simulink. The state space model derived from the identified second order ARX model parameters is

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{b}u + \mathbf{e}r\,;\;\; y = \mathbf{c}^{\mathrm{T}}\mathbf{x}\,, \tag{1}$$

where

$$\mathbf{A} = \begin{bmatrix} -83.0583 & 218.2890 \\ -204.9014 & 76.7292 \end{bmatrix},\; \mathbf{b} = \begin{bmatrix} -1.4349 \\ -1.708 \end{bmatrix}, \mathbf{e} = \begin{bmatrix} -0.2359 \\ -0.0477 \end{bmatrix},\; \mathbf{c}^{\mathrm{T}} = \begin{bmatrix} 1 & 0 \end{bmatrix}.$$

3. Review of Periodic Output Feedback Controller

Consider a linear continuous-time invariant state space model:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{b}u;\;\; y = \mathbf{c}^{\mathrm{T}}\mathbf{x}\,, \tag{2}$$

where $\mathbf{x} \in \Re^{n}, \mathrm{u} \in \Re^{m}, \mathrm{y} \in \Re^{p}$ and $\mathbf{A}, \mathbf{b}$ and $\mathbf{c}^{\mathrm{T}}$ are constant matrices. It is assumed that $\left(\mathbf{A}, \mathbf{b}, \mathbf{c}^{\mathrm{T}}\right)$ is controllable and observable. Assume that output measurements are available from the system in equation (1) at time instants $t = k\tau$, where k=0,1,2..... . Now design an output injection gain matrix $\mathbf{G}$, such that the eigen values of $\left(\mathbf{\Phi}_{\tau} + \mathbf{G}\mathbf{c}^{\mathrm{T}}\right)$ are inside the unit circle. For the system $(\mathbf{\Phi}_{\tau}, \mathbf{\Gamma}_{\tau}, \mathbf{c}^{T})$ the control signal is generated according to

$$\begin{aligned} &\mathrm{u(t)} = \mathrm{K}_{l}\, \mathrm{y}(\mathrm{k}\tau), \\ &\mathrm{k}\tau + l\Delta \le \mathrm{t} < \mathrm{k}\tau + (\,l + 1\,)\Delta,\; \mathrm{K}_{l+\mathrm{N}} = \mathrm{K}_{l} \end{aligned} \tag{3}$$

for $l = 0,1,....\mathrm{N}-1,$ where a sampling interval τ is divided into N subintervals $\Delta = \dfrac{\tau}{\mathrm{N}}$ and N is equal to or greater than the controllability index of $\left(\mathbf{\Phi}_{\tau}, \mathbf{\Gamma}_{\tau}\right)$. Note that the sequence of gain matrices $\left\{\mathrm{K}_{0}, \mathrm{K}_{1}, \mathrm{K}_{2}, ...\mathrm{K}_{N-1}\right\}$, when substituted into equation (3), generates a time-varying, piecewise constant output feedback gain $\mathrm{K}(t)$ for $0 \le t \le \tau$. To see the relationship between the gain sequence $\left\{\mathrm{K}_{l}\right\}$ and closed loop behavior collect the gain matrices K_{l} into one matrix

$$\mathbf{K} = \begin{bmatrix} \mathrm{K}_{0} & \mathrm{K}_{1} & \cdots & \mathrm{K}_{N-1} \end{bmatrix}^{\mathrm{T}}$$

By applying a control input $\mathrm{u}(t)$ as calculated in equation (3), a state space representation for the closed loop system sampled at the rate of $\dfrac{1}{\tau}$ is

$$\mathbf{x}(k+1)=\mathbf{\Phi}^{\mathrm{N}}\mathbf{x}(k)+\mathbf{\Gamma}\,\mathbf{K}\,\mathbf{c}^{\mathrm{T}}\mathbf{x}(k), \tag{4}$$

where

$$\mathbf{\Gamma}=\left[\mathbf{\Phi}^{\mathrm{N\text{-}1}}\mathbf{\Gamma}\ \mathbf{\Phi}^{\mathrm{N\text{-}2}}\mathbf{\Gamma}\quad \mathbf{\Phi}^{\mathrm{N\text{-}3}}\mathbf{\Gamma}\quad .\ .\ .\ .\quad \mathbf{\Gamma}\right]$$

If $(\mathbf{\Phi},\mathbf{\Gamma})$ system is controllable and $\left(\mathbf{\Phi}_{\tau},\mathbf{c}^{\mathrm{T}}\right)$observable, one can first choose an output injection gain **G** to place the eigen values of $\left(\mathbf{\Phi}_{\tau}+\mathbf{G}\mathbf{c}^{\mathrm{T}}\right)$in the desired locations and then compute the gain sequence $\left\{\mathrm{K}_{1}\right\}$ such that $\mathbf{\Gamma K}=\mathbf{G}$ is satisfied.

Let $(\mathbf{\Phi}_{\tau},\mathbf{\Gamma}_{\tau},\mathbf{c}^{\mathrm{T}})$ be the discrete time system obtained with by sampling the system in equation (1) at a rate 1/τ. Let the characteristics polynomial of $\mathbf{\Phi}_{\tau}$ be represented as

$$p(\Phi_{\tau})=S^{n}+\sum_{i=0}^{n-1}a_{i}S^{i} \tag{5}$$

Let the controllable canonical form of the system (1) be ($\mathbf{\Phi}_{\tau,\mathrm{c}},\ \mathbf{\Gamma}_{\tau,\mathrm{c}},\ \mathrm{C}_{\mathrm{c}},\ \mathrm{Z}_{\mathrm{c}}$). If the state feedback gain $F_{c}=[f_{c,0}\quad f_{c,0}\quad \cdots\quad f_{c,n\text{-}1}\ ]$ is designed for this system such that the eigen spectrum of the closed loop system ($\Phi_{\tau,\mathrm{c}}+\Gamma_{\tau,\mathrm{c}}F_{c}$) is $\Lambda=\{\lambda_{1,\ \ldots,}\ \lambda_{\mathrm{n}}\}$ then it can be easily shown that

$$p(\Phi_{\tau,\mathrm{c}}+\Gamma_{\tau,\mathrm{c}}F_{c})=S^{n}+\sum_{i=0}^{n-1}(a_{i}+f_{c,i})S^{i} \tag{6}$$

Similarly, the observable canonical representation of system (1) is ($\mathbf{\Phi}_{\tau,\mathrm{o}},\ \mathbf{\Gamma}_{\tau,\mathrm{o}},\ \mathrm{C}_{\mathrm{o}},\ \mathrm{Z}_{\mathrm{o}}$). The output injection gain $G_{o}=[g_{o,0},\ g_{o,0},\ \ldots,\ g_{o,n}]^{T}$ is computed ($\Phi_{\tau,\mathrm{o}}+G_{o}\mathrm{C}_{\mathrm{o}}$) has the same eigenspectrum Λ as of the state closed loop controllable canonical form with state feedback gain F_{c} then

$$p(\Phi_{\tau,\mathrm{o}}+G_{o}\mathrm{C}_{\mathrm{o}})=p(\Phi_{\tau,\mathrm{c}}+\Gamma_{\tau,\mathrm{c}}F_{c}) \tag{7}$$

$$S^{n}+\sum_{i=0}^{n-1}(a_{i}+g_{o,i})S^{i}=S^{n}+\sum_{i=0}^{n-1}(a_{i}+f_{c,i})S^{i}$$

Comparing the coefficients of S^{i}, i = 0,……, n-1, it can be seen that $g_{o,i}=f_{c,i}$, i=0,…….., n-1,

$$G_{o}=F_{c}^{T} \tag{8}$$

The state feedback gain and output injection gain that have the same effect on the original system ($\Phi_\tau, \Gamma_\tau, c^T, x$) as F_C and G_O have on its controllable and observable canonical forms respectively, can be computed as

$$\begin{aligned} F &= F_C T_C \\ G &= T_O^{-1} G_O \end{aligned} \tag{9}$$

Now using, the relation between F and G may be derived as

$$G = T_O^{-1} (F T_C^{-1})^T \tag{10}$$

The periodic output feedback gain that would result in the same closed loop poles as a given by state feedback is computed from this,

$$\mathrm{K} = \Gamma^{-1} T_O^{-1} (F T_C^{-1})^T \tag{11}$$

This periodic output feedback gain **K** would result in the eigen values of the closed loop system ($\Phi_\tau + \Gamma \mathrm{K} c^T$) to be the same as those obtained from state feedback F, i.e., eigen vales of the closed loop system ($\Phi_\tau + \Gamma_\tau \mathrm{F}$).

4. Controller Design

The periodic output feedback controller is designed to reduce the amplitude of vibration of the cantilever beam at resonance. A stabilizing output injection gain is designed as explained in Section 3 for the system $(\Phi_\tau, \Gamma_\tau, c^T)$, such that the eigen values of $(\Phi_\tau + \mathrm{G}c^T)$ lie inside the unit circle.
Where

$$\tau = 0.01 \text{ sec and } \Delta = 0.0025 \text{ sec, N} = 4$$

$$\Phi_\tau = \begin{bmatrix} -0.7320 & 1.0000 \\ -0.9387 & -0.0000 \end{bmatrix} \quad \Gamma_{\tau,b} = \begin{bmatrix} -0.0158 \\ -0.0025 \end{bmatrix}$$

$$\Gamma_{\tau,e} = \begin{bmatrix} -0.0008 \\ 0.0013 \end{bmatrix} \quad \mathbf{c}^T = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

$$\mathrm{F} = [0.4157 \quad 20.6308] \text{ and}$$

$$\mathrm{G} = [-0.0574 \quad 0.2684]^T.$$

The open loop response, response with state feedback gain obtained in simulation is shown in Fig. 2.

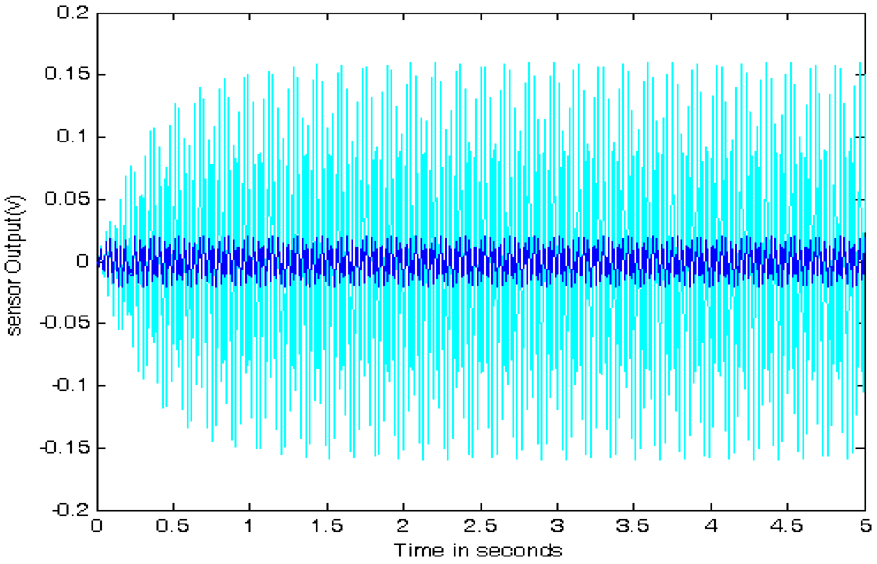


Fig. 2. Response to excitation at first natural frequency: - uncontrolled and controlled with state feedback gain.

The periodic output feedback gain obtained by solving equation (11) is

$$K = [48.6133 \quad 24.5878 \quad -5.6442 \quad -35.0216]$$

The open loop response, response with periodic output feedback gain obtained in simulation is shown in Fig. 3.

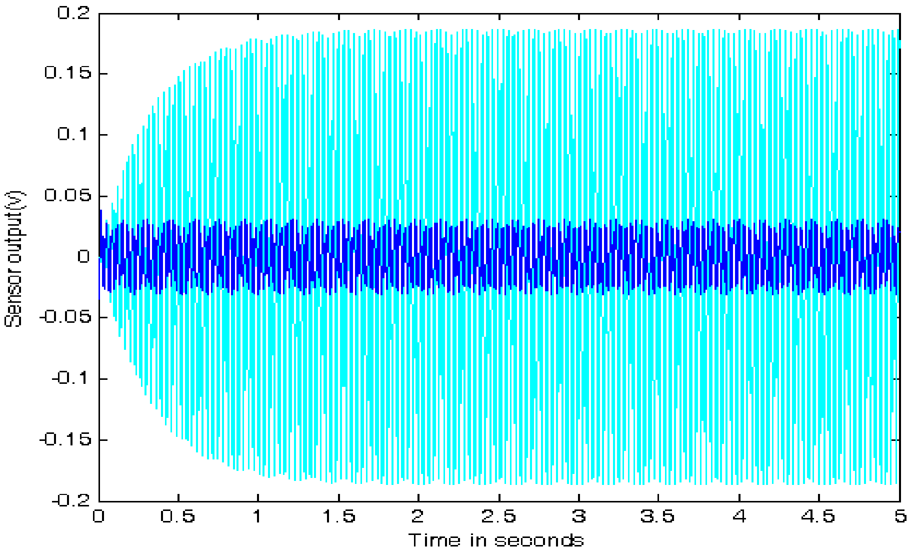


Fig. 3. Response to excitation at first natural frequency: - uncontrolled and controlled with Periodic output feedback gain.

5. Experimental Implementation Using Microcontroller

The periodic output feedback controller designed in section 4 is experimentally evaluated for its performance in suppressing the first vibration mode of smart cantilever beam using KEIL software.

The experimental set up with microcontroller (AT89C51) interface for implementing the controller is shown in Fig. 4. A sinusoidal excitation with first natural frequency and amplitude of 5V peak to peak is applied to the disturbance actuator which makes the beam to vibrate at resonance. The sensor output is fed to the piezo sensing system which consists of high quality charge to voltage signal conditioning amplifier with variable gain. The conditioned piezosensor signal is given as analog input to the level shifter for shifting the negative cycle to positive which is sampled at τ s by sample and hold and applied to Analog to Digital converter (ADC). The control signal is generated in microcontroller (AT89C51) as per the equation (11) and is applied as input to the Digital to Analog converter (DAC). The output of the DAC is connected to actuator via piezo actuation system. The uncontrolled and controlled response is shown in Fig. 5. In Fig. 5. initially the control signal is not applied latter the control is switched ON which suppresses the vibration.

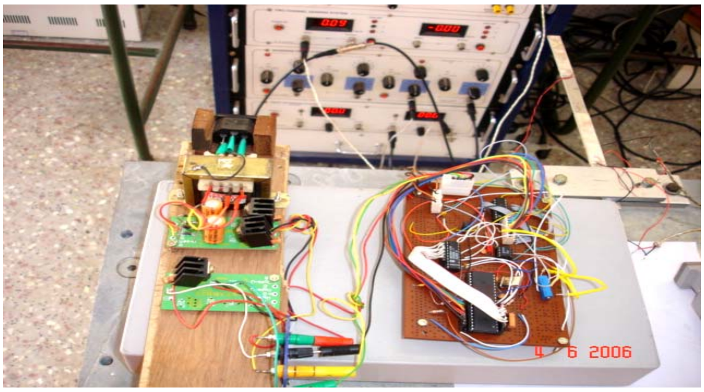


Fig. 4. Experimental set up with microcontroller interface.

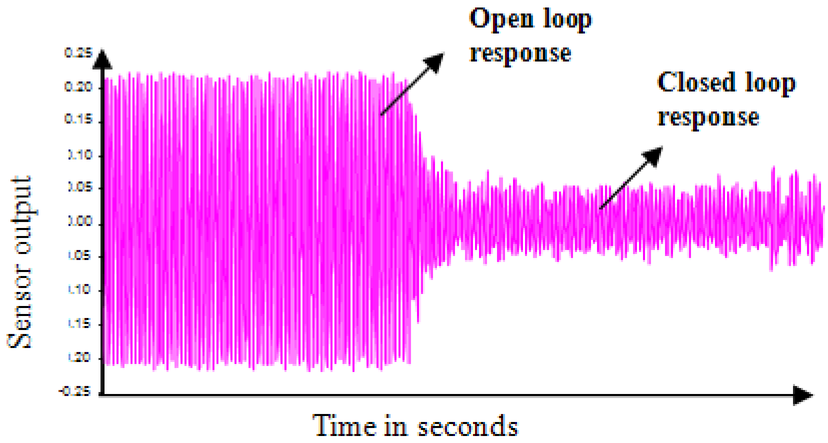


Fig. 5. Response to excitation at first natural frequency: - uncontrolled and controlled with Periodic output feedback gain (Experimental).

6. Conclusion

A periodic output feedback controller has been designed from the state feedback gain to control the first mode vibration of a cantilever beam using piezo actuator. The simulation and experimental results demonstrate the performance of the controller for vibration suppression. The hardware used for implementing the controller is very simple and cost effective.

References

[1]. Chopra I., Review of state of art of smart structures and integrated systems, *AIAA J.,* 40, 2002, pp. 2145–2187.

[2]. Hanagud, S., Obal, M. W., and Callise, A. J., Optimal vibration control by the use of piezoceramic sensors and actuators, *Journal of Guidance, Control and Dynamics*, 15, 5, 1992, pp. 1199-1206.

[3]. Narayanan S., Balamurugan V., Finite element modeling of piezo laminated smart Structures for active vibration control with distributed sensors and actuators, *J. Sound Vib.,* 262, 2003, pp. 529–562.

[4]. Gabbert U., Koppe H. and Trajkov T. N., Controller design for engineering smart structures based on finite element models, *Smart Structures and Materials*, *Proc. SPIE,* 4693, 2002, pp. 430–439.

[5]. Chengli He C. and Ratneshwar Jha, Experimental evaluation of augmented UD identification based vibration control of smart structures, *J. Sound Vib.,* 274, 2003, pp. 1065–1078.

[6]. S. M. Yang, C. A. Jeng, Structural vibration suppression by concurrent piezoelectric sensor and actuator, *Smart Materials and Structures*, 5, 6, 1996, pp. 806-813.

[7]. D. Ezhilarasi, M. Umapathy, B. Banddyopadhayay, Design and experimental evaluation of piecewise output feedback control for structure vibration suppression, *Journal of Smart Materials and Structures*. 15, 2006, pp. 1927-1938.

[8]. M. Umapathy, B. Bandopadhyay, Vibration control of flexible beam through smart structure concept using periodic output feedback, *Journal of System Science*, Vol. 26, No. 1, 2000, pp. 43-66.

[9]. S. Janardhanan and B. Bandyopadhyay, A New Method for the Computation of Periodic Output Feedback Gain for SISO Control System, Proc. *International Symposium on Process Systems Engineering and Control*, held in IIT Bombay on 3rd-4th January 2003, pp. 277-280.

Sensors & Transducers Journal

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

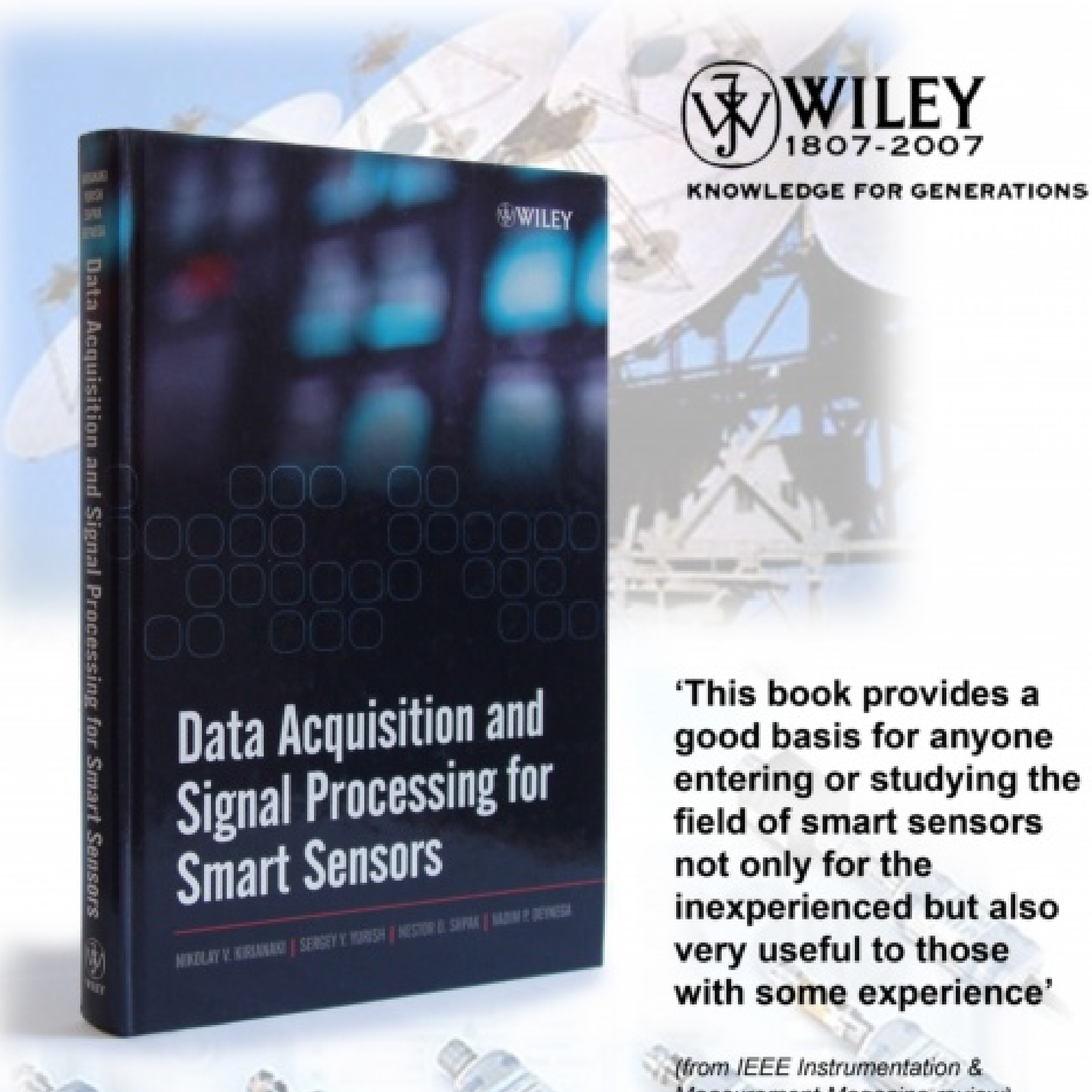
- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors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

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 6-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

Advertising Information

Advertising orders and enquires may be sent to sales@sensorsportal.com Please download also our media kit: http://www.sensorsportal.com/DOWNLOADS/Media_Kit_2008.pdf


WILEY
Data Acquisition and Signal Processing for Smart Sensors
NIKOLAY V. KIRIANAKI | SERGEY Y. YURISH | NESTOR O. SHPAK | VADIM P. DEYNEGA