ISSN 1726-5479

SENSORS & TRANSDUCERS

9/09 vol. 108

IEEE

TEDS Sensors, IEEE 1451 Standards

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 108, Issue 9
September 2009

www.sensorsportal.com

ISSN 1726-5479

Editors-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

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

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

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

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

Editor for Asia-Pacific
Mukhopadhyay, Subhas, Massey University, New Zealand

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
Baliga, Shankar, B., General Monitors Transnational, USA
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
Benachaiba, Chellali, Universitaire de Bechar, Algeria
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
Chavali, Murthy, VIT University, Tamil Nadu, India
Chen, Jiming, Zhejiang University, China
Chen, Rongshun, National Tsing Hua University, Taiwan
Cheng, Kuo-Sheng, National Cheng Kung University, Taiwan
Chiang, Jeffrey (Cheng-Ta), Industrial Technol. Research Institute, 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, Jianning, Jiangsu Polytechnic 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, Univ.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
Haider, Mohammad R., Sonoma State University, USA
Hashsham, Syed, Michigan State University, USA
Hasni, Abdelhafid, Bechar University, Algeria
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
Jiang, Wei, University of Virginia, USA
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
Sapozhnikova, Ksenia, D.I.Mendeleyev Institute for Metrology, Russia

Kim, Min Young, Kyungpook National University, 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, University "Mediterranea" of Reggio Calabria, Italy
Mounir, Ben Ali, University of Sousse, Tunisia
Mulla, Imtiaz Sirajuddin, National Chemical Laboratory, Pune, India
Neelamegam, Periasamy, Sastra Deemed University, India
Neshkova, Milka, Bulgarian Academy of Sciences, Bulgaria
Oberhammer, Joachim, Royal Institute of Technology, Sweden
Ould Lahoucine, Cherif, 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
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 Univ. 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 Inst. 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
Vazquez, 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 Univ. 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
Yang, Xiaoling, University of Georgia, Athens, GA, USA
Yaping Dan, Harvard University, USA
Ymeti, Aurel, University of Twente, Netherland
Yong Zhao, Northeastern University, China
Yu, Haihu, Wuhan University of Technology, China
Yuan, Yong, Massey University, New Zealand
Yufera Garcia, Alberto, Seville University, Spain
Zagnoni, Michele, University of Southampton, UK
Zamani, Cyrus, Universitat de Barcelona, Spain
Zeni, Luigi, Second University of Naples, Italy
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
Zhang, Xueji, World Precision Instruments, Inc., USA
Zhong, Haoxiang, Henan Normal University, China
Zhu, Qing, Fujifilm Dimatix, Inc., USA
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 on CD. Copyright © 2009 by International Frequency Sensor Association. All rights reserved.

Sensors & Transducers Journal

Contents

Volume 108
Issue 9
September 2009

www.sensorsportal.com

ISSN 1726-5479

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. 108, Issue 9, September 2009, pp. 31-39

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Dynamic Characterization of MEMS Scanners

[1]Çağlar ATAMAN, [1]Hüseyin R SEREN, [2]Harald SCHENK, [1]Hakan ÜREY
[1]Koç University, Electrical Engineering and Optical Microsystems Laboratory,
34450 Istanbul, Turkey
[2] Fraunhofer-IPMS, Maria-Reiche-Str. 2 01109 Dresden, Germany
[1]Tel.: +902123381474, +902123381548,
E-mail: hurey@ku.edu.tr

Received: 17 July 2009 /Accepted: 21 September 2009 /Published: 28 September 2009

Abstract: A simple yet precise optical characterization technique for beam scanning devices is proposed. The method uses a single photodetector to measure various dynamic characteristics of scanning devices, including frequency, scan angle, scan phase, and the mechanical quality factor, given that the scan waveform is known. A quantitative performance analysis and a set of experimental characterization results are presented. Experimentally 0.007 % scan angle measurement accuracy is demonstrated and it is shown that it can be improved. *Copyright © 2009 IFSA.*

Keywords: MEMS, Scanner characterization

---

1. Introduction

Micro-electro-mechanical system (MEMS) scanning mirrors have proven to be a versatile and effective solution for ultra-small yet high resolution display and imaging systems. This mirror is connected to small flexures allowing it to oscillate vertically and/or horizontally to capture (imaging) or reproduce (display) an image pixel-by-pixel allowing high resolution display and imaging systems. The literature on microscanner technology is very rich with devices targeting head mounted displays [1-2], hand-held projectors [3-4], endoscopic imaging/tomography [5-6], spectroscopy [7], and various other applications. High precision, controllability, and low jitter are essential for high resolution scanning applications; hence precise dynamic characterization and real-time monitoring of device performance is crucial.

Characterization and dynamic control of microscanners require a position feedback. This feedback can be provided through various methods. Piezo-resistive sensors [8], capacitive readout [9], and electromagnetic back-emf monitoring are some of the feedback mechanisms employed in conventional microscanners. Characterizations of such devices only require a monitor device to observe/record the output of the position feedback mechanism. However, most microscanners lack position feedback, since integrating such mechanisms with the device significantly increases device complexity. Experimental characterization of such devices requires complex external optical measurement techniques, such as interferometry [10] or scanning and point-wise vibrometry [11].

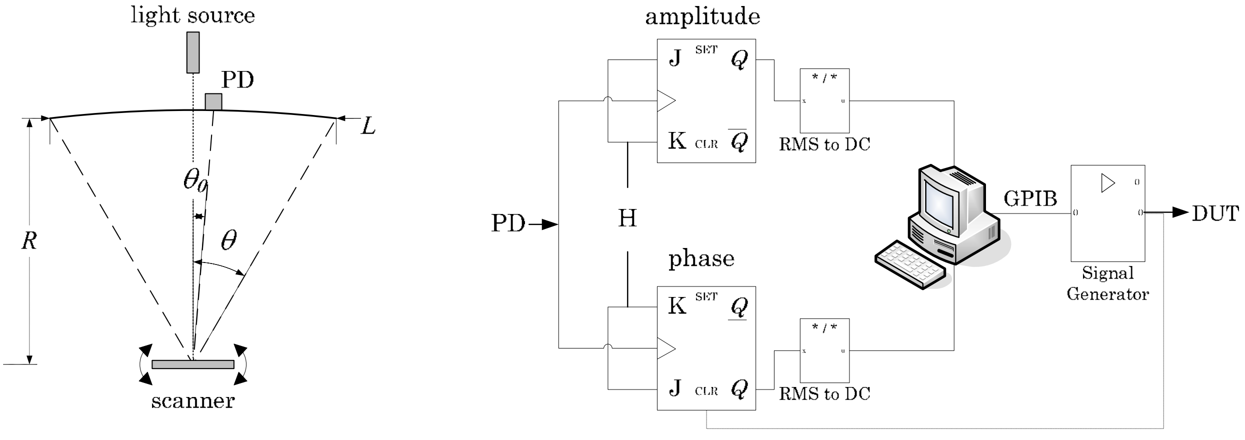
In this paper we present a simple but high precision microscanner characterization technique that needs a single photodetector only to simultaneously measure the frequency, scan angle and scan phase of an oscillating microscanner, assuming that the scan waveform of the scanner is known. This principle can be applied to characterization of microscanners with sinusoidal oscillation or polygon type scanners with linear velocity, and can easily be integrated into miniaturized scanning engines for precise position control. In addition, the same technique can also be used for damping characterization. Section 2 describes the general layout of the measurement system, the measurement principle. Experimental amplitude, phase and damping measurements are also included.

2. Measurement Setup

A simple schematic measurement system is given in Fig. 1a. Fig. 1b shows the layout of the required electronics and the scanner drive. Main measurement device is a Hamamatsu S5049 bi-cell photodetector placed on the scan line of an oscillating microscanner. This is a widely available photo-IC used for print start timing detection for laser printers, and copiers. Each crossing of a laser beam from the detector creates a digital pulse whose rise-time is independent of the size and the speed of the laser beam. While the microscanner is oscillating, the output of the photodetector is a periodic train of short pulses. Fall time of the detector output is independent of scanner frequency, scan-angle and spot size, and is equal to 20 ns. The output of the detector is fed into the clock input of two toggle-mode negative edge-triggered J-K flip-flops, one of which is always active (for scan amplitude measurement), and the other is activated in sync with the scanner drive signal (for phase measurement). Therefore, the amplitude flip-flop changes state at each detector pulse (Fig. 3c), while the phase flip-flop changes state once every two detector pulses (Fig. 3e). Both flip-flops produce a square wave with different duty cycles. Characteristics of device oscillations can be extracted by performing different waveform measurements on the signals produced by the flip-flops. Next we discuss how dynamic response and quality factor measurements for microscanners are performed. For the test measurements, slow axis of a 2D electromagnetically actuated MEMS microscanner developed for a head mounted display application is used (Fig. 2).

2.1. Scan Angle Measurement

In the scan angle measurement configuration, the photodetector is placed at an off-center point on the scan line. Hence, the duty-cycle of the square waveform produced by the amplitude flip-flop is not 50 % and depends on the position of the detector on the scan line and the optical scan angle. Assuming oscillations are purely sinusoidal –a very good approximation for MEMS microscanners due to their high quality factors–, the optical scan angle can be computed using angle between the center of the scan line and the photodetector and the flip-flop output waveform parameters.



(a) (b)

Fig. 1. (a) Microscanner Characterization Setup (PD: Bi-cell photodetector); (b) Microscanners are driven by signal generator via the GPIB interface, and frequency, and drive voltage domain response of a microscanner can be obtained automatically.

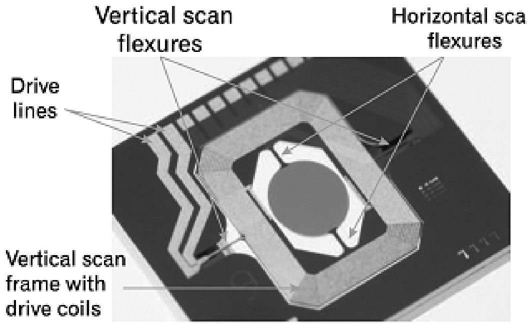


Fig. 2. Electromagnetically driven 2D torsional microscanner [2].

The time required for the beam to travel from the center of the scan line onto the detector (t_0) is given by (the timing convention used for the derivation is shown in Fig. 3):

$$t_0 = \frac{T\left(\frac{1}{2} - \delta_1\right)}{2}, \tag{1}$$

where, δ_1 is the measured duty cycle of the amplitude flip-flop output, and T is the measured oscillation period. The ratio between the detector position (θ_0) and the maximum zero-to-peak optical scan angle (θ) can then be computed using (1) and Fig. 3:

$$\frac{\theta_0}{\theta} = \sin\left(\frac{2\pi}{T} t_0\right) = \sin\left(\frac{\pi}{2} - \pi\delta_1\right) \tag{2}$$

Equation (2) states that the scan angle depends only on the detector angular position and the duty cycle of the amplitude flip flop output square-wave. Therefore, the accuracy of the measurements is determined by the precision of the measurement of these two factors.

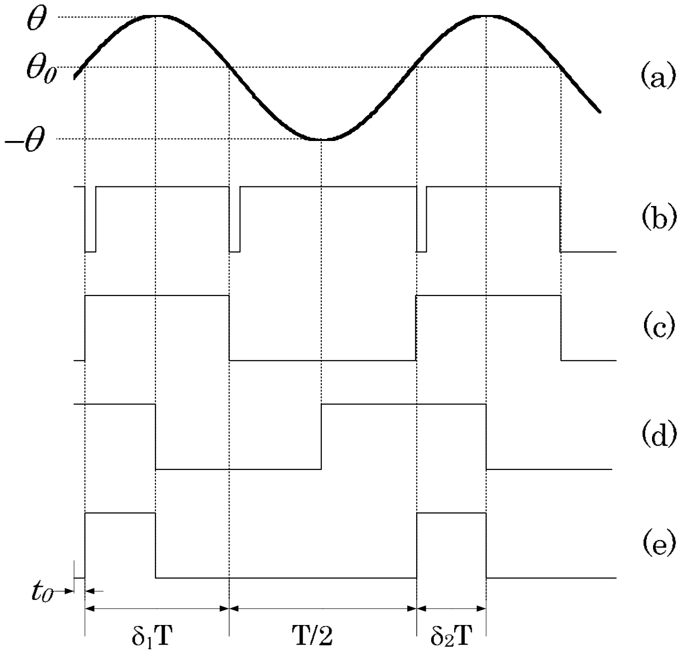


Fig. 3. Timing convention (a) Scanner Position, (b) Bi-cell Photodetector Output, (c) Flip-flop Output for Amplitude, (d) Scanner Drive Sync Signal (e) Phase Flip-flop output for Phase.

Calibration: The size of the scan line and scanner-detector separation (L and R in Fig. 1a) is initially measured manually with a ruler or caliper to determine θ. Then, the detector is placed onto the scan line, close to the center, so that minimum measurable scan angle is minimized. θ_0 is then computed by the software from the measured θ, t_0 and δ_1 using (2). Since a long scan line can be measured quite accurately, the ambiguity introduced by the calibration error is rather small. For integrated measurements, the detector position can initially be set for once with high precision.

Duty cycle measurement: Frequency, phase and duty-cycle of the flip-flop output may be measured by an oscilloscope or by a PC with DAQ interface. Either way, an analog-to-digital conversion of the waveform is to be performed. Discretization of the waveform introduces an error to the duty cycle measurement. Average error in measuring $\delta_1 T$ product for N measurements is equal to

$$\varepsilon = \pm \frac{1}{N * f_{sampling}} \tag{3}$$

Ambiguity that arises due to this error can be computed using (3):

$$\theta \pm \Delta\theta = \frac{\theta_0}{\sin\left(\frac{2\pi}{T}(t_0 \pm \varepsilon)\right)} \tag{4}$$

Equation 4 indicates that A/D conversion error is related to the scanner frequency and the sampling rate. For small θ_0/θ values, measurement error is relatively high; as θ_0/θ approaches unity measurement error decreases significantly. Averaging is also very effective in reducing the measurement error, especially for characterization purposes, where measurement time is of secondary importance compared to accuracy. Even for real-time applications, averaging is acceptable if time constants of changes (temperature, humidity, pressure) are large in comparison to the averaging time, as it is for displays, spectrometers, and barcode readers.

Discretization is the fundamental source of ambiguity for small scan angle or low sampling rate measurements. The effect of discretization can be eliminated by analog measurement of the duty cycle of the flip flop outputs. A true RMS-to-DC converter IC (Analog Devices AD536A) was employed for analog measurement of the duty cycle. The output of the flip flop was fed to the converter. Then, the duty cycle of the flip flop output was calculated from the measured rms value. In this technique the error limits are determined by the characteristics of the converter, and strongly depend on the peripheral circuitry and the duty cycle of the signal to be measured. Table I is a list of theoretical and experimental measurement errors for different detector positions and sampling frequencies without averaging. For digital sampling method, the measurement error is reduced by increasing the sampling rate and the offset ratio. Accuracy of the analog method, however, does not depend on these factors and is limited only by the measurement error of the RMS-to-DC converter. The measurement accuracy can be improved by using a faster photodetector and by placing the detector near the edge of the scan line. Further improvements are possible by averaging multiple cycles and the signal generated can be used for closed-loop control of the scanner. The accuracy of the scan angle and phase measurement can be increased to be in the order of 1/10,000 as demonstrated in high-resolution printing applications.

Table 1 presents digital and analog noise levels for two different offset ratios and three different sampling rates. The theoretical digital noise levels are calculated using (4). The digital noise is found by measuring the standard deviation of the pulse width in a number of periods and dividing it by the mean pulse width. The analog noise is found by measuring the standard deviation of the mean dc level over a number of periods and dividing it by the mean of the mean dc level. As can be interpreted from the Table 1, the higher the sampling ratio the better the precision is; and as aimed the analog digital level is not affected by the sampling ratio.

Table 1. Theoretical and experimental measurement error for different detector positions and sampling frequencies.

ADC Rate	Offset Ratio	Frequency (Hz)	Digital (theory, N=5)	Digital (exp)	Analog (exp)
1 Ms/sec	0.1	406	0.5 %	0.55 %	0.043 %
2 Ms/sec	0.1	406	0.2 %	0.18 %	0.037 %
5 Ms/sec	0.1	406	0.1 %	0.13 %	0.046 %
1 Ms/sec	0.9	406	0.024 %	0.036 %	0.031 %
2 Ms/sec	0.9	406	0.008 %	0.015 %	0.035 %
5 Ms/sec	0.9	406	0.004 %	0.007 %	0.026 %

Proposed measurement technique can be adapted to different device response characterization experiments. Frequency response of a microscanner device can be obtained by sweeping the scanner excitation frequency quasi-statically with constant or adaptive steps, and recording the scan angle of the device at each step. For excitation-amplitude response experiments, same procedure can also be applied. For both measurements, the user should pay attention to wait long enough before taking data at each step, so that the device reaches steady state after the frequency or voltage is updated.

2.2. Phase Measurement

A phase measurement method is developed by using a square wave with 50 % duty cycle, which has the same frequency and the same phase with the driving signal. Such a signal is often available from signal generator trigger outputs. The square wave is fed to the $\overline{Clear}$ input pin of the flip flop. Thus, the output became dependent on both the crossing time of the bi-cell and the fall time of the input signal. The phase difference between the driving input and the microscanner scan angle can be derived from the duty cycle of the flip-flop output.

$$\Phi = \frac{2\pi}{T}\left(\frac{T}{2} - \delta_2 T - t_0\right), \tag{5}$$

where Φ stands for the phase difference between the drive signal and the microscanner scan angle, $\delta_2 T$ is the new duty-cycle and period product, and t_0 is as defined in Eq. (1). The presence of the offset t_0 brings some limitations to the possible measurable phases which can be found as:

$$\frac{2\pi}{T}t_0 < \Phi_{measurable} < \frac{2\pi}{T}\left(\frac{T}{2} - t_0\right) \tag{6}$$

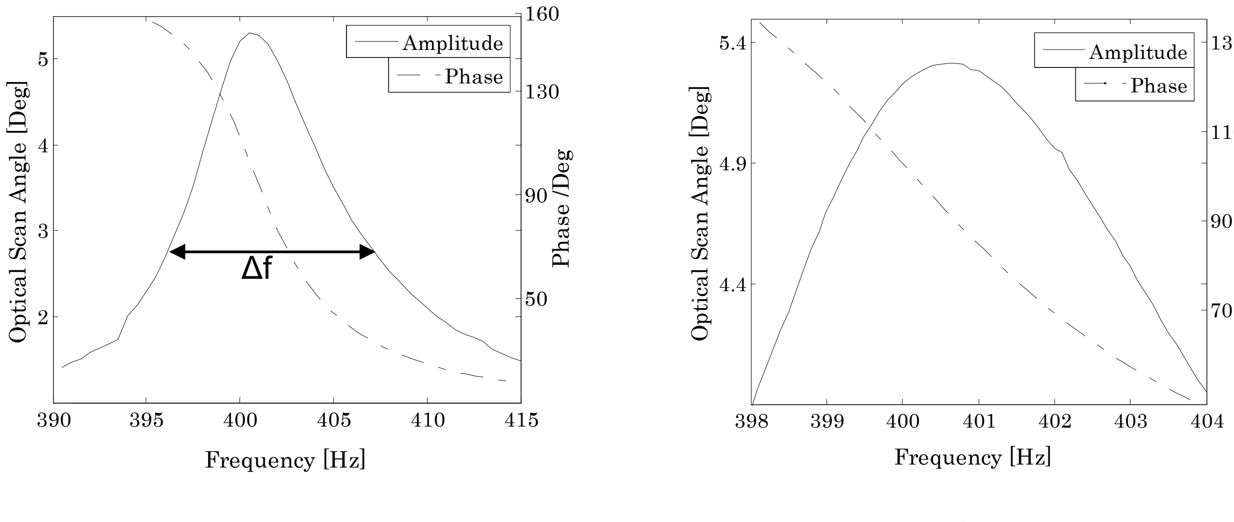
If the amplitude measurement is not required, then the photodetector can be placed in the middle of the scan line, i.e., t_0=0 and the phase computation can be simplified as:

$$\Phi = \pi(1 - 2\delta_2) \tag{7}$$

For this case, full span, from 0 to π phase difference, can be measured.

This phase measurement technique can be employed for closed-loop control of the scanner using the phase feedback, which allows the control via phase-lock-loop (PLL).

Fig. 4 illustrates the amplitude and phase of the frequency response of a torsional scanner shown in Fig. 2 measured with the proposed technique. The frequency response for nonlinear/hysteretic systems can also be measured with this technique [12].



(a)

(b)

Fig. 4. Amplitude and phase of the frequency response of a MEMS scanner measured with the proposed technique. **(a)** Broad range measurement with offset ratio = 0.1 **(b)** Measurement around the resonance peak with offset ratio = 0.9. The measured device is the slow axis of a 2D electromagnetically actuated MEMS microscanner developed for a head mounted display application [2].

2.3. Damping Measurement

For linear underdamped systems, the easiest method to determine the quality factor of the system is using the 3 dB bandwidth 'Δf' of the frequency response, illustrated in Fig. 4a. The 3 dB bandwidth and the quality factor are related through the following expression.

$$Q = \frac{2\pi I_m f_0}{b} = \frac{f_0}{\Delta f}, \tag{8}$$

where b is the damping factor and I_m is the effective mass moment of inertia of the scanner [13].

For an unforced microscanner with sufficient mechanical mode separation and pure velocity dependent damping, the scan angle can be expressed as

$$\theta(t) = e^{-\xi t}\theta_0 \cos(2\pi f_0 t + \varphi), \tag{9}$$

where, ξ is the decay rate of the oscillations, θ_0 is the initial maximum scan angle, f_0 is the damped natural frequency, and φ is an arbitrary phase factor.

Fig. 5 shows the damped oscillations together with the flip-flop output signal when the detector is placed at θ_0. Damping of a scanner can be determined with this setup in two different ways. As θ decreases due to damping, duty-cycle of the flip-flop output shrinks. By evaluating the scan angle using (2) for every period in Fig. 5, a sequence of exponentially decaying angle values are obtained. Decay rate of the oscillations can be computed by fitting a negative exponential to this sequence. Thus, the damped oscillation can be expressed in the form of (9). This method requires the storage and non-real-time processing of flip-flop output. This method is particularly useful in damping characterization of low-Q (e.g., Q<100) devices. Damping measurement result for the same microscanner is given in Fig. 6. The quality factor was measured to be 61.57, while the reference measurement result performed with a Laser Doppler Vibrometer (LDV) is 61.60.

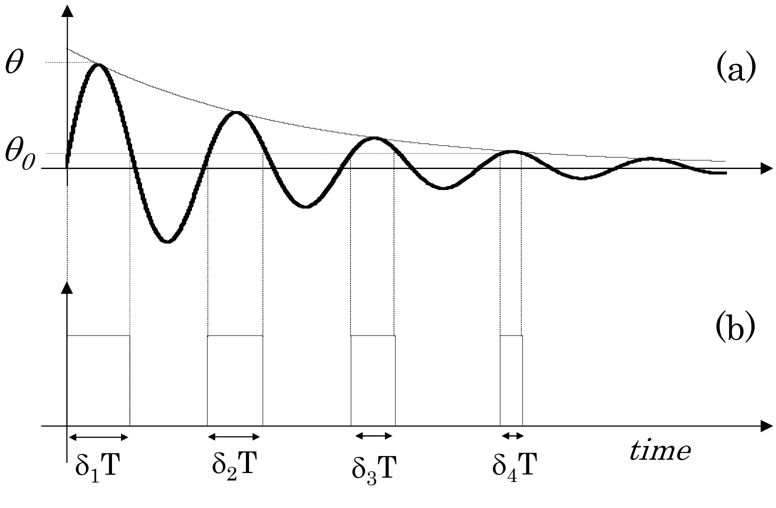


Fig. 5. Damped oscillations of an unexcited microscanner, and corresponding amplitude flip-flop output.

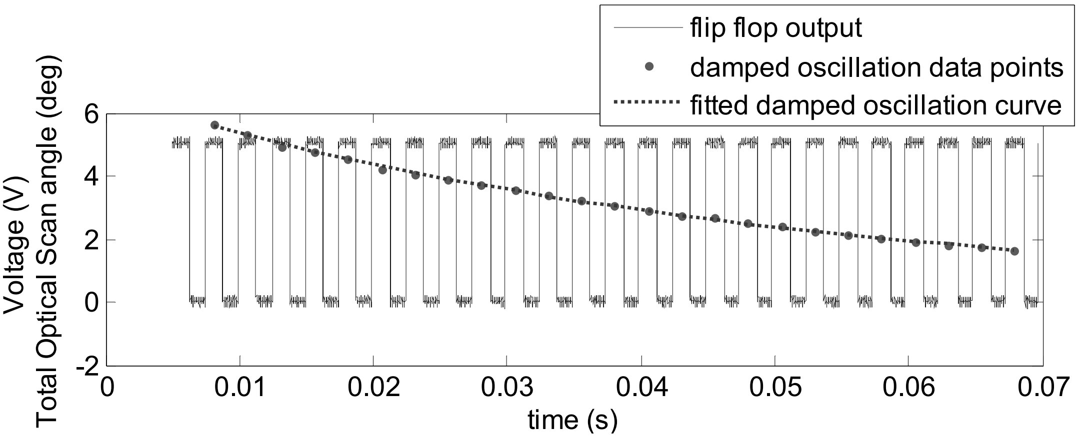


Fig. 6. Experimental damping measurement results. Scanner drive signal is stopped and simultaneously the amplitude flip-flop output is recorded with a data acquisition card. Then, for each period, the scan angle is computed from its duty cycle. This procedure can also be performed in real time using a timer circuit.

For high-Q scanners, a simpler technique can be used. It takes many cycles for this type of devices to settle. Therefore the time required for θ to scale down to θ_0 can be approximated by the number of periods of the square-wave times the damped oscillation period. This method introduces a fractional time measurement error in the order of 1/Q. For high-frequency scanners, Q is often large and the error is negligible.

3. Conclusions

A simple yet precise characterization technique is demonstrated for microscanners to measure scan amplitude and phase, damping, and frequency response assuming the deflection waveform is a sinusoid. The setup utilizes a single photodetector and a data analysis interface. For laboratory experiments, this interface may be GPIB or DAQ. Proposed measurement method can also be integrated with a miniaturized scanning engine, in which data analysis can be simply performed by a microcontroller. Main advantages of the technique are simplicity, spot-size independent detection, and flexibility. In addition to scanner characterization, the technique can be used to provide amplitude or phase feedback for closed-loop control of scanning systems. The accuracy of the scan angle and phase measurement can be increased to be in the order of 1/10000.

Acknowledgements

H. Urey gratefully acknowledges the support from TÜBA-GEBİP award.

References

[1]. H. Urey, Retinal Scanning Displays, Encyc. of Optical Engineering, Marcel-Dekker, 2003.

[2]. Arda D. Yalçınkaya, Hakan Urey, Dean Brown, Tom Montague, Randy Sprague, Two-axis Electromagnetic Microscanner for High Resolution Displays, *IEEE J. Microelectromechanical Systems*, Vol. 15, 4, Aug. 2006, p. 786-794.

[3]. Y. C. Ko, J. W. Cho, Y. K. Mun, H. G. Jeong, W. K. Choi, J. W. Kim, Y. H. Park, J. B. Yoo, J. H. Lee, Eye-type Scanning Mirror with Dual Vertical Combs for Laser Display, *Sensors and Actuators A*, Vol. 126, 2006, pp. 218–226.

[4]. K. Roscher, H. Grätz, H. Schenk, A. Wolter, H. Lakner, Low Cost Projection Device with a 2D Resonant Microscanning Mirror, *SPIE Proc. of MOEMS Display and Imaging Systems II*, Vol. 5348, 2004, pp. 22-31.

[5]. H. Miyajami, K. Murakami, M. Katashiro, MEMS Optical Scanners for Microscopes, *IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 10, No. 3, 2004, pp. 514-527.

[6]. D. Aguirre, W. Piyawattanametha, P. R. Herz, L. Fan, Y. Chen, J. G. Fujimoto, M. C. Wu, Two-axis MEMS Scanning Catheter for Ultrahigh Resolution Three-dimensional and Face Imaging, *Optics Express*, Vol. 15, No. 5, 2007, pp. 2445-2453.

[7]. F. Zimmer, H. Grueger, A. Heberer, A. Wolter, H. Schenk, Development of an NIR Microspectrometer Based on a MOEMS Scanning Grating, *SPIE Proc. of MEMS, MOEMS and Micromachining*, Vol. 5455, 2004, pp. 9-18.

[8]. D. W. Wine, M. P. Helsel, L. Jenkins, H. Urey, T. D. Osborn, Performance of a Biaxial MEMS-Based Scanner for Microdisplay Applications, *Proc. of SPIE on MOEMS and Miniaturized Systems*, Vol. 4178, 2000, pp. 186-196.

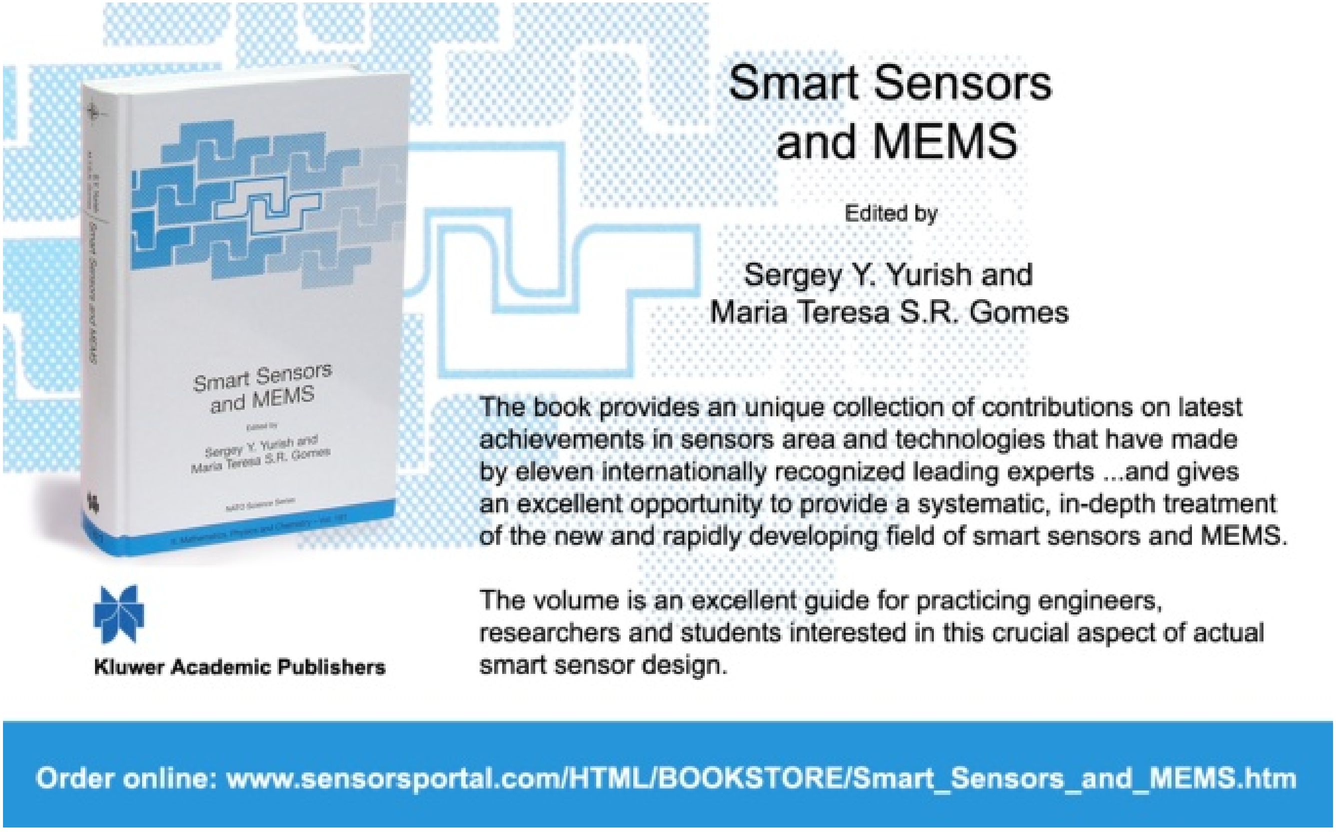
[9]. T. Kiessling, A. Wolter, H. Schenk, H. Lakner, Bulk Micromachined Quasistatic Torsional Micromirror, *Proc. of SPIE on MOEMS and Miniaturized Systems IV*, Vol. 5346, 2004, pp. 193-202.

[10].L. Salbut, et. al., Interferometric Methods for Static and Dynamic Characterizations of Micromembranes for Sensing Functions, *Proc of SPIE on Optical Micro- and Nanometrology in Manufacturing Technology*, Vol. 5458, 2004, pp. 16-24.

[11].E. M. Lawrence, K. Speller, D. Yu, Laser Doppler Vibrometry for Optical MEMS, *Proc. of SPIE on 5th Int. Conf. on Vibration Measurements with Laser Techniques*, Vol. 4827, 2002, pp. 80-87.

[12].C. Ataman, H. Urey, Modeling and Characterization of Comb Actuated Resonant Microscanners, *Journal of Micromechanics and Microengineering*, Vol. 16, 2006, pp. 9-16.

[13].S. Senturia, Microsystem Design, *Kluwer*, Boston, 2001.



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. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

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:

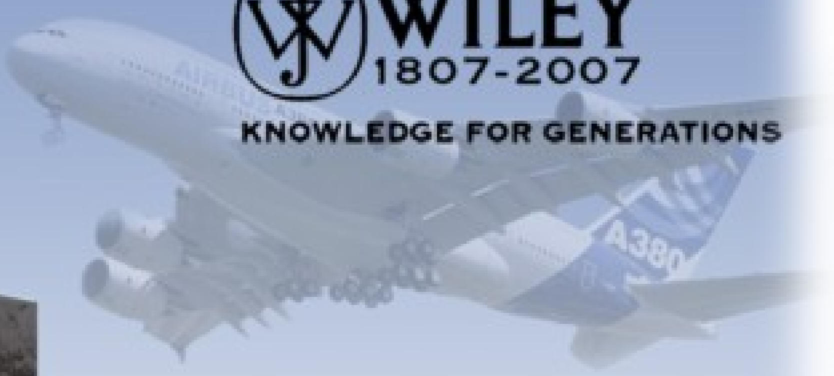
- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors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

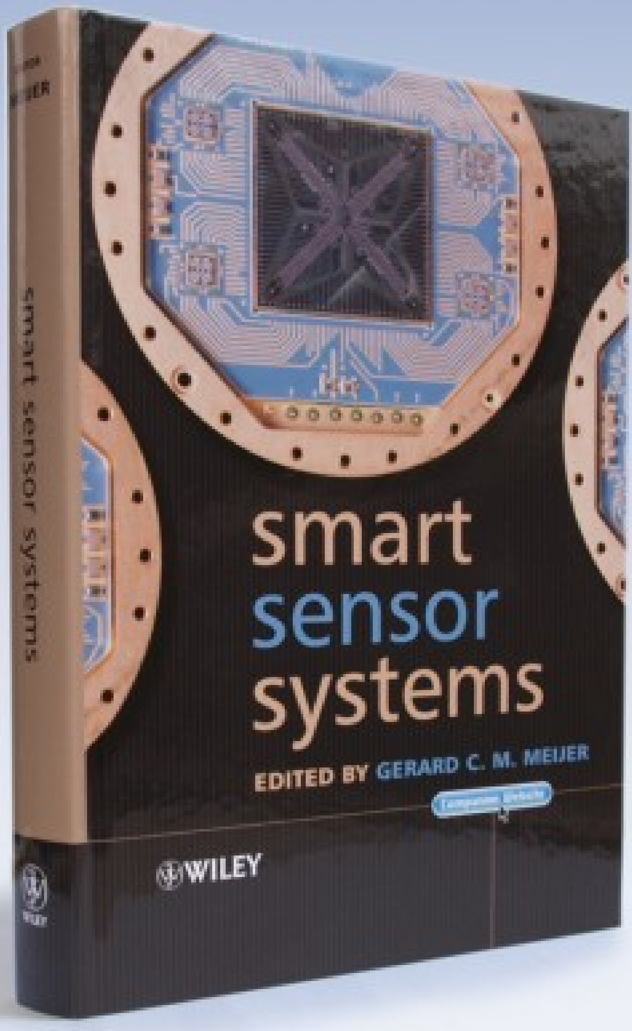
Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 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_2009.pdf


AIRBUS
A380


smart sensor systems
EDITED BY GERARD C. M. MEIJER
WILEY
MEIJER
smart sensor systems
WILEY


UTI03
A99A
UTI03
A99C