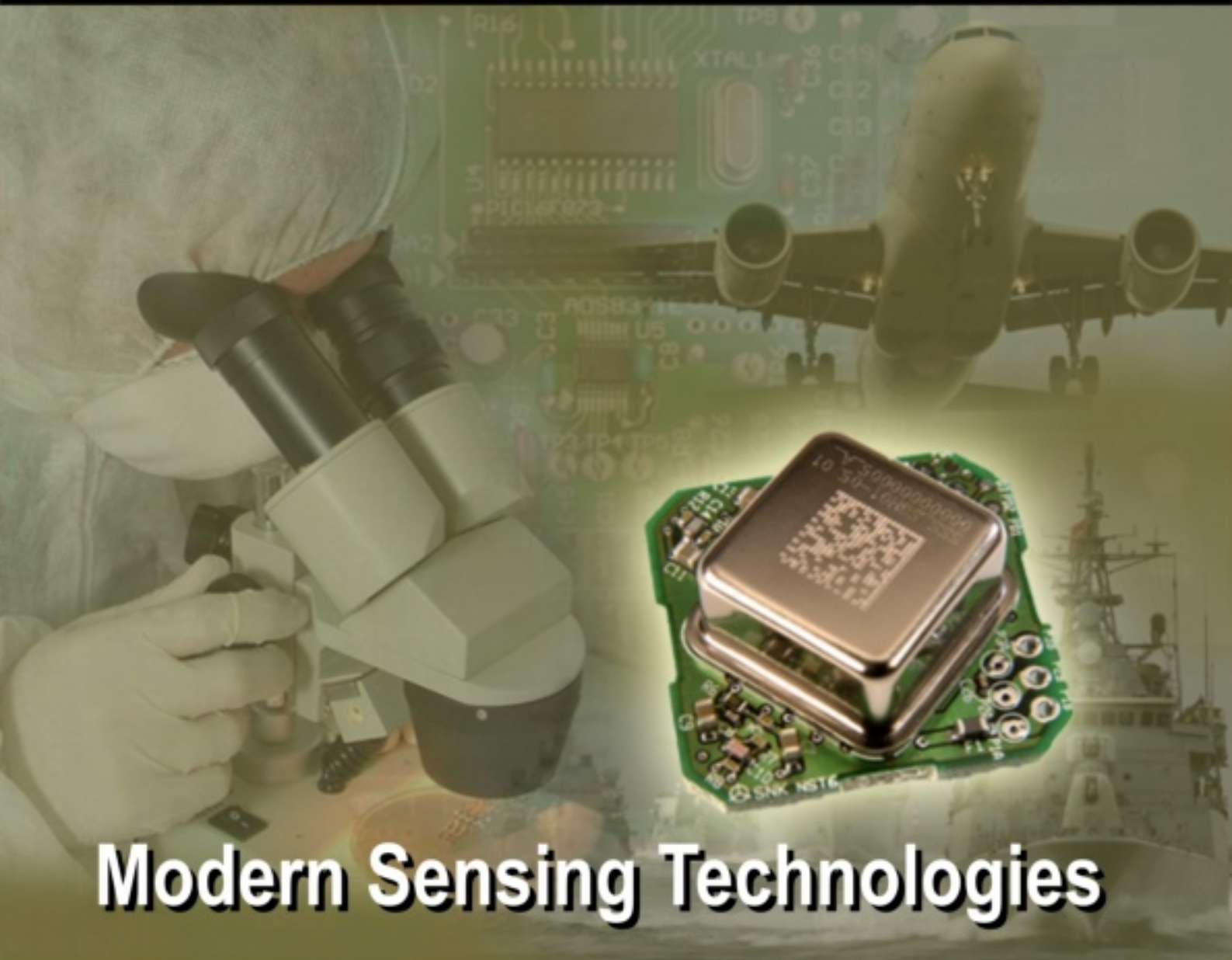


ISSN 1726-5749

SENSORS & TRANSDUCERS

vol. 90
Special
4/08



Modern Sensing Technologies

International Frequency Sensor Association Publishing





Sensors & Transducers

Special Issue
April 2008

www.sensorsportal.com

ISSN 1726-5479

Editor-in-Chief: Sergey Y. Yurish

Guest Editors: Subhas Chandra Mukhopadhyay and Gourab Sen Gupta

Editors for Western Europe

Meijer, Gerard C.M., Delft University of Technology, The Netherlands
Ferrari, Vittorio, Università 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, Northern University of Engineering, Malaysia
Annamalai, Karthikeyan, 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, Vygtantas, 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
Cerde 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, Université 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
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

Dickert, Franz L., Vienna University, Austria
Dieguez, Angel, University of Barcelona, Spain
Dimitropoulos, Panos, University of Thessaly, Greece
Ding Jian, Ning, Jiangsu University, China
Djordjević, 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
Rodriguez, Angel, Universidad Politecnica de Catalunya, Spain
Rothberg, Steve, Loughborough University, UK
Sadana, Ajit, University of Mississippi, USA

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 Seteal, 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
Raouf, 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 Politècnica de Catalunya, Spain
Sadeghian Marnani, Hamed, TU Delft, The Netherlands
Sandacci, Serghei, Sensor Technology Ltd., UK
Sapozhnikova, Ksenia, D.I.Mendeleyev Institute for Metrology, Russia
Saxena, Vibha, Bhabha 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
Shmali, Yuriy, Kharkiv National University of Radio Electronics, Ukraine
Silva Grao, 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, 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
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

Contents

Volume 90
Special Issue
April 2008

www.sensorsportal.com

ISSN 1726-5479

Special Issue on Modern Sensing Technologies

Editorial

Modern Sensing Technologies

Subhas Chandra Mukhopadhyay and Gourab Sen Gupta 1

Sensors for Medical/Biological Applications

Characteristics and Application of CMC Sensors in Robotic Medical and Autonomous Systems

X. Chen, S. Yang, H. Natuhara K. Kawabe, T. Takemitsu and S. Motojima 1

SGFET as Charge Sensor: Application to Chemical and Biological Species Detection

T. Mohammed-Brahim, A.-C. Salaün, F. Le Bihan 11

Estimation of Low Concentration Magnetic Fluid Weight Density and Detection inside an Artificial Medium Using a Novel GMR Sensor

Chinthaka Gooneratne, Agnieszka Łekawa, Masayoshi Iwahara, Makiko Kakikawa and Sotoshi Yamada 27

Design of an Enhanced Electric Field Sensor Circuit in 0.18 μm CMOS for a Lab-on-a-Chip Bio-cell Detection Micro-Array

S. M. Rezaul Hasan and Siti Noorjannah Ibrahim 39

Wireless Sensors

Coexistence of Wireless Sensor Networks in Factory Automation Scenarios

Paolo Ferrari, Alessandra Flammini, Daniele Marioli, Emiliano Sisinni, Andrea Taroni 48

Wireless Passive Strain Sensor Based on Surface Acoustic Wave Devices

T. Nomura, K. Kawasaki and A. Saitoh 61

Environmental Measurement OS for a Tiny CRF-STACK Used in Wireless Network

Vasanth Iyer, G. Rammurthy, M. B. Srinivas 72

Ubiquitous Healthcare Data Analysis And Monitoring Using Multiple Wireless Sensors for Elderly Person

Sachin Bhardwaj, Dae-Seok Lee, S.C. Mukhopadhyay and Wan-Young Chung 87

Capacitive Sensors

Resistive and Capacitive Based Sensing Technologies

Winncy Y. Du and Scott W. Yelich 100

A Versatile Prototyping System for Capacitive Sensing <i>Daniel Hrach, Hubert Zangl, Anton Fuchs and Thomas Bretterklieber</i>	117
The Physical Basis of Dielectric Moisture Sensing <i>J. H. Christie and I. M. Woodhead</i>	128
Sensors Signal Processing	
Kalman Filter for Indirect Measurement of Electrolytic Bath State Variables: Tuning Design and Practical Aspects <i>Carlos A. Braga, João V. da Fonseca Neto, Nilton F. Nagem, Jorge A. Farid and Fábio Nogueira da Silva</i>	139
Signal Processing for the Impedance Measurement on an Electrochemical Generator <i>El-Hassane Aglzim, Amar Rouane, Mustapha Nadi and Djilali Kourtiche</i>	150
Gas Sensors	
Gas Sensing Performance of Pure and Modified BST Thick Film Resistor <i>G. H. Jain, V. B. Gaikwad, D. D. Kajale, R. M. Chaudhari, R. L. Patil, N. K. Pawar, M. K. Deore, S. D. Shinde and L. A. Patil</i>	160
Zirconia Oxygen Sensor for the Process Application: State-of-the-Art <i>Pavel Shuk, Ed Bailey, Ulrich Guth</i>	174
Image Sensors	
Measurement of Digital Camera Image Noise for Imaging Applications <i>Kenji Irie, Alan E. McKinnon, Keith Unsworth, Ian M. Woodhead</i>	185
Calibration-free Image Sensor Modelling Using Mechanistic Deconvolution <i>Shen Hin Lim, Tomonari Furukawa</i>	195
Miscellaneous	
Functional Link Neural Network-based Intelligent Sensors for Harsh Environments <i>Jagdish C. Patra, Goutam Chakraborty and Subhas Mukhopadhyay</i>	209
MEMS Based Pressure Sensors – Linearity and Sensitivity Issues <i>Jaspreet Singh, K. Nagachenchaiah, M. M. Nayak</i>	221
Slip Validation and Prediction for Mars Exploration Rovers <i>Jeng Yen</i>	233
Actual Excitation-Based Rotor Position Sensing in Switched Reluctance Drives <i>Ibrahim Al-Bahadly</i>	243
A Portable Nuclear Magnetic Resonance Sensor System <i>R. Dykstra, M. Adams, P. T. Callaghan, A. Coy, C. D. Eccles, M. W. Hunter, T. Southern, R. L. Ward</i>	255
A Special Vibration Gyroscope <i>Wang Hong-wei, Chee Chen-jie, Teng Gong-qing, Jiang Shi-yu</i>	267
An Improved CMOS Sensor Circuit Using Parasitic Bipolar Junction Transistors for Monitoring the Freshness of Perishables <i>S. M. Rezaul Hasan and Siti Noorjannah Ibrahim</i>	276

Sensing Technique Using Laser-induced Breakdown Spectroscopy Integrated with Micro-droplet Ejection System <i>Satoshi Ikezawa, Muneaki Wakamatsu, Joanna Pawlat and Toshitsugu Ueda</i>	284
A Forward Solution for RF Impedance Tomography in Wood <i>Ian Woodhead, Nobuo Sobue, Ian Platt, John Christie</i>	294
A Micromachined Infrared Sensor for an Infrared Focal Plane Array <i>Seong M. Cho, Woo Seok Yang, Ho Jun Ryu, Sang Hoon Cheon, Byoung-Gon Yu, Chang Auck Choi</i>	302
Slip Prediction through Tactile Sensing <i>Somrak Petchartee and Gareth Monkman</i>	310
Broadband and Improved Radiation Characteristics of Aperture-Coupled Stacked Microstrip Antenna for Mobile Communications <i>Sajal Kumar Palit</i>	325
The Use of Bragg Gratings in the Core and Cladding of Optical Fibres for Accurate Strain Sensing <i>Ian G. Platt and Ian M. Woodhead</i>	333

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>

Measurement of Digital Camera Image Noise for Imaging Applications

¹Kenji IRIE, ²Alan E. McKINNON, ²Keith UNSWORTH, ¹Ian M. WOODHEAD

¹Lincoln Ventures Ltd, P.O. Box 133, Lincoln, Christchurch 7640, New Zealand

Tel.: ++64-3-325-3712, fax ++64-3-325-3712,

² Applied Computing Group, Lincoln University, Canterbury, New Zealand

E-mail: {iriek, woodhead}@lvl.co.nz, {mckinnon, unsworth}@lincoln.ac.nz

Received: 15 October 2007 /Accepted: 20 February 2008 /Published: 15 April 2008

Abstract: Noise within captured images from digital cameras is unavoidable and can confound or reduce the performance of an image-based application. It is present in the captured photons, generated in the sensor electronics, and an inherent part of the digital signal processing. A measure of image noise can allow an algorithm to fine tune its parameters to minimize the effects of noise, or could be used in a filter to remove noise prior to image analysis. This paper presents an overview of image noise and describes a method for measuring noise quantity for use in image-based applications. *Copyright © 2008 IFSA.*

Keywords: Image analysis, Noise measurement, CCD image sensor, CMOS image sensor

1. Introduction

Advances in digital image sensors have led to their ubiquitous use in many industrial and consumer applications. Industrial applications often attempt to extract useful information from the digital images, which is limited in robustness and performance because of image noise. The sources of image noise are well documented [1-3], with the number of sources increasing with camera complexity [4, 5]. The analysis of modelled image noise becomes more difficult with increasing camera complexity, so we present a method of noise analysis that does not require a model and is dependent only upon output images from a camera. A background on image noise is provided, followed by the method used for measuring noise to characterize a camera's effective noise output, suitable for an image or video based application.

2. Sources of Camera and Image Noise

A summary of sources of camera and image noise is provided. Existing terminology used for sources of image sensor noise varies and is inconsistent, depending upon the author and the approach taken for its analysis. Multiple definitions will be provided in the text where appropriate.

2.1. Offset Fixed-Pattern Noise

Offset fixed-pattern noise (FPN) arises from variations due to device mismatches during sensor fabrication and their associated dark currents. Dark currents are leakages produced by surface generation and minority carriers thermally generated in the sensor well, and in variations between transistors in active-pixel elements. The expected value for a pixel's dark current is constant for a given operating condition though it increases with exposure time. FPN is the total pixel-to-pixel variation occurring in an image sensor, and is alternatively referred to as Dark Signal Non-Uniformity or DSNU [1, 3, 6-8]. FPN is temperature dependent and is measurable in dark conditions.

2.2. Photo Response Non-Uniformity

The pixel output to a given illumination is dependent on the variations in geometry, substrate material, microlenses, and any transistors that may be present around the pixel. The variations are nearly impossible to eliminate and the resulting effect is described as Photo Response Non-Uniformity (PRNU). It is dependent upon illumination and is prominent under high illumination levels [3]. It is also referred to as gain fixed-pattern noise.

2.3. Shot Noise

Shot noise is a Poisson process that arises from random fluctuations in sampling when discrete quanta are measured. Significant shot noise sources in an image sensor are in the capturing of photons in the photon-detection stage, in the temporal variation of dark currents, and in transistor semiconductors. Sources of shot noise generated by independently moving charges, such as in current movement in metallic conductors, exhibit long-range correlations [9] and are considered as minor contributors to the total shot noise present in an image sensor.

The number of dark-current shot noise electrons doubles with every 8° C rise in temperature [1, 10], and is proportional to the pixel integration time. Photon shot noise is dependent upon the mean number of captured photons, and therefore increases with sensor irradiance.

2.4. Readout Noise

Readout noise describes the total temporal noise added during the process of reading a signal out of an image sensor, from the photoreceptor through to the analogue-to-digital conversion process. It includes pixel reset noise, thermal noise sources (Johnson-Nyquist), $1/f$ (flicker) noise sources, and other minor contributors such as conductor shot noise.

The resetting of the charge sense capacitor to a reference voltage level introduces noise from thermal fluctuations, often described as ' kT/C ' or reset noise. A common method used to reduce the capacitor-reset variations is correlated double sampling (CDS) [1, 11]. CDS samples the noise value on the sense capacitor after reset, and subtracts it from the sample of pixel data after charge transfer. There are

more complex implementations of CDS used [12], however the details of these are beyond the scope of this paper.

Any electrical conductor exhibits equilibrium fluctuations due to the random thermal motion of the charge carriers. This thermal, or Johnson-Nyquist noise, occurs regardless of the voltage applied to the conductor [9, 13].

$1/f$ or ‘flicker’ noise is generated in the photo-diodes and in the low-bandwidth analogue operation of MOS transistors due to imperfect contacts between two materials [1, 13]. It is pink-coloured, and the level of noise is dependent upon the frequency of the pixel sampling rate.

2.5. Column Noise

Many CMOS image sensors use column amplifiers to enable high pixel data rates [1]. Variations between transistor amplifiers result in both offset and gain variations between columns of an image, increasing spatial variation along the rows of an image.

2.6. Demosaicing

Many single-sensor color cameras use color filter arrays (CFAs) to restrict the pixel bandwidths to a particular range in the optical spectrum. A commonly used CFA is the Bayer matrix that reduces each pixel’s bandwidth to approximately 1/3 of the visible wavelengths of light. A method of colour interpolation called demosaicing is then employed to generate full-colour values at each pixel in an image [14]. The demosaicing process used to interpolate the color data for each pixel is generally manufacturer dependent and unknown.

2.7. Quantization

Digital images are often quantized to 8-16 bits per color channel for export from the camera. Where the quantization step is very small compared to variations within the image, the quantization process adds noise to the image according to the following equation [15]:

$$\hat{\sigma}_{\text{quantization}}^2 = \frac{q^2}{12} \quad (1)$$

where q is the quantizing step. For $q=1$ $\sigma_{\text{quantization}} = 0.29$.

2.8. Other Considerations

Many digital cameras apply a series of digital filters such as edge enhancement, color balancing, gain, and gamma correction that all affect the noise characteristics of the image¹. Lossy image compression is often applied that reduces both color and edge acuity. CCDs are also prone to smearing and blooming due to the limited charge capacity of the photodiodes. This may cause some correlation of data along columns of pixels.

In this work the digital camera filters have been disabled or set to neutral and images have been

¹ The common brightness or black level adjustment simply alters the DC offset of the image and does not affect its noise detail.

transferred in the RGB format².

3. Measurement of Image Noise

The sources of noise described in Section 2 can be segmented into three general categories for the purpose of noise measurement: spatial noise, temporal noise, and total image noise. Spatial noise has a dependency upon orientation of the analysis due to column noise. Measurement of spatial noise is calculated along the rows of an image to ensure that any column noise is included in the noise analysis.

3.1. Spatial Noise

Spatial noise is exhibited as variations between the pixels in an image given a constant illumination across the sensor, and is dominated by offset FPN at low illuminations and by PRNU at high illuminations [16]. Knowledge of spatial noise is useful in applications where images are averaged prior to analysis (e.g., low-light applications like astronomy where multiple images may be captured to increase effective exposure time). Images of spatial noise can be achieved by averaging a series of images containing smooth areas of constant reflectance, removing the temporal variations. The generation of an image of spatial noise, $\overline{image(i, j)}$, is given by:

$$\overline{image(i, j)} = \frac{\sum_{k=1}^n P_k(i, j)}{n}, \quad (2)$$

where n is the number of images. $P_k(i, j)$ is the pixel value for row i , column j in the k^{th} image. A second-order polynomial can be fitted to each row of $\overline{image(i, j)}$ to describe any optical effects such as shadowing or vignetting. The residuals after subtraction of the polynomial-fitted data can be concatenated for each row and the unbiased standard deviation σ calculated, giving the value of the spatial noise σ_{spatial} .

3.2. Temporal Noise

Temporal noise varies between images and is dependent on illumination. Knowledge of temporal noise is useful in applications where images are compared or subtracted before analysis (e.g., in a subtraction-based motion detection algorithm). Temporal noise can be measured by taking the average value of the variations exhibited by a pixel over a series of images. The equation for temporal noise

σ_{temp} for a given sensor irradiance is therefore:

$$\sigma_{\text{temp}} = \frac{\sum_{y=1}^j \sum_{x=1}^i \sigma(x, y)}{i \times j}, \quad (3)$$

² Although transferred to the computer in RGB format, the camera may not necessarily operate internally in the RGB space.

where i and j are the number of rows and columns respectively and $\sigma(x, y)$ is the unbiased standard deviation of the pixel value at (x, y) over n images.

3.3. Total Noise

The total noise in an image is the combined effect of all spatial and temporal noises present in an image. It is useful in applications where a single image is used for processing (e.g., in an edge detection algorithm). To measure total image noise, the process of fitting a second-order polynomial to each of the n images is applied in the same fashion as the calculation of spatial image noise σ_{spatial} in $\overline{\text{image}(i, j)}$. A series of unbiased standard deviations for each row of the k^{th} image of the n image set is calculated, giving σ_k . The average of σ_k over all n images gives σ_{total} .

4. Experiment

The measurement of image noise requires a series of static images containing areas of constant detail. The Gretag Macbeth Color Checker (GMB chart) provides a useful series of colour patches suitable for noise measurement. The lower portion of the chart consists of grey-scale panels that provide a range of reflectances (3.1 to 90.0 CIE Y values) that can be used for analysis of both colour and monochromatic cameras. The cameras were defocused to reduce the effect of high-frequency content in the observed panels that could affect the noise analysis. The illumination sources (combined fluorescent and incandescent³) were positioned above the camera and directed towards the chart such that the image was free from direct specular reflection. A single set of images for each camera was used for noise measurement analysis.

Standard statistical methods can determine an appropriate number of samples (either pixels or images) required to achieve a desired confidence interval and error for the observed sample mean [17].

For a population with an unknown mean μ and unknown standard deviation σ , a confidence interval for the population mean, based on a random sample of size n , is:

$$\bar{X} \pm t \times \frac{s}{\sqrt{n}}, \quad (4)$$

where \bar{X} is the mean of the sample population, s is the estimated standard deviation derived from the sample population, and t is the $(1-C)/2$ critical value for the t -distribution with $n-1$ degrees of freedom where C is the desired confidence interval.

A standard confidence interval of 95% is used for this research. It was observed that s is rarely greater than five in most digital video images (with cameras in 'auto' mode, data values 0-255) in canonical lighting conditions. A suitable maximum level of error is one quantization step in the digital data, which is a value of one. From expression (4) above, this yields the following upper bound for the mean error:

³ Each light source was adjusted to provide similar camera RGB response for a grey-scale image.

$$1 \geq t \times \frac{5}{\sqrt{n}} \quad (5)$$

The t -distribution is a function of n and C . Using standard t -distribution tables and choosing $n=100$ give a value of 1.962. Substituting these values into the right hand side of (5) gives a value of 0.981 and inequality (5) is satisfied. Note that this holds only for estimated standard deviations less than or equal to 5. Therefore an appropriate sample size to achieve a 95% confidence interval for noise measurement is 100 samples.

Experiments were conducted at an ambient temperature of approximately 22° C. All digital camera effects such as colour balance and gamma were disabled in the experiments, although the method for noise measurement described in Section 3 is suitable for any fixed camera settings.

4.1. CMOS Camera Noise

Fig. 1 illustrates the spatial, temporal, and total noise measurement for the CMOS camera (Table 1) as described in Section 3, with each of the three colour channels showing similar noise responses.

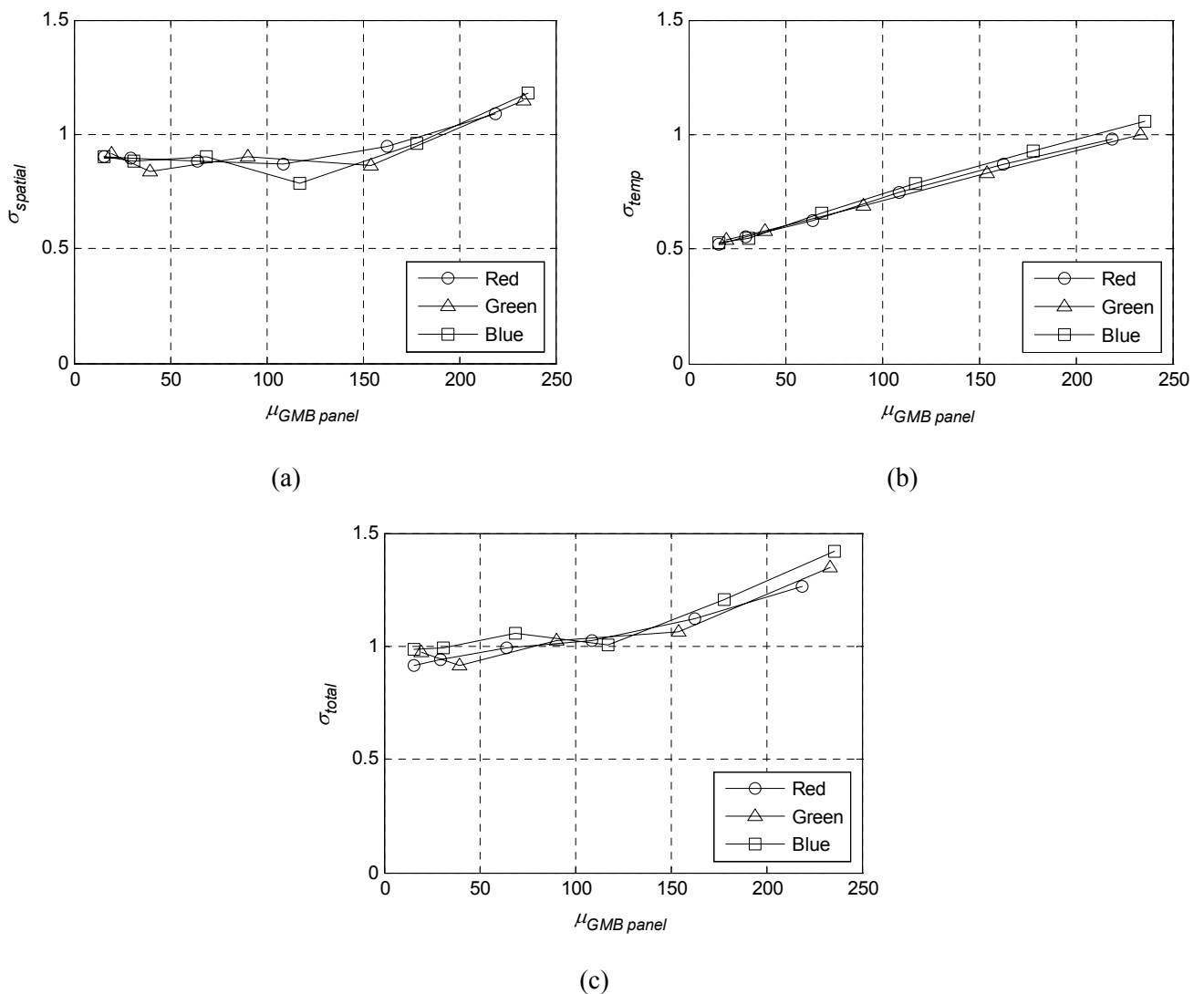


Fig. 1. CMOS camera noise: spatial (a), temporal (b), total (c).

Table 1. UEYE UI1210-C camera details.

Parameter	Value
Sensor type	½" CMOS (Bayer array)
Native resolution	640 x 480
Video mode	24-bit RGB (8-bits/channel)
Interface	USB 2.0

4.5. CCD Camera Noise

Fig. 2 illustrates the spatial, temporal, and total noise measurements for the CCD camera (Table 2). Experiments found that the green channel of the CCD camera was limited to values below approximately 150 when all digital effects were disabled. The cause of this effect is unknown and the illumination was set to ensure the green channel measurements for all channels were below 150.

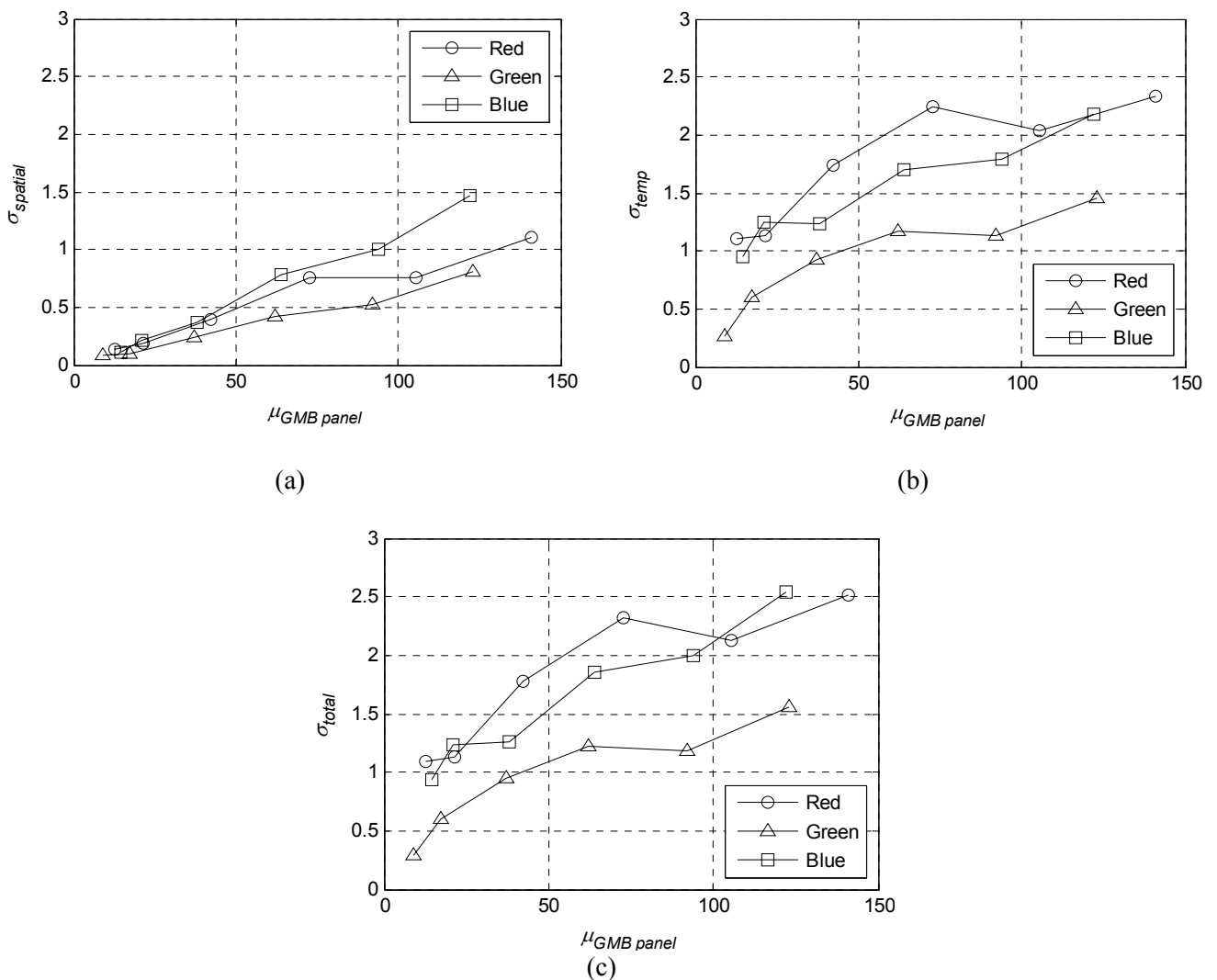


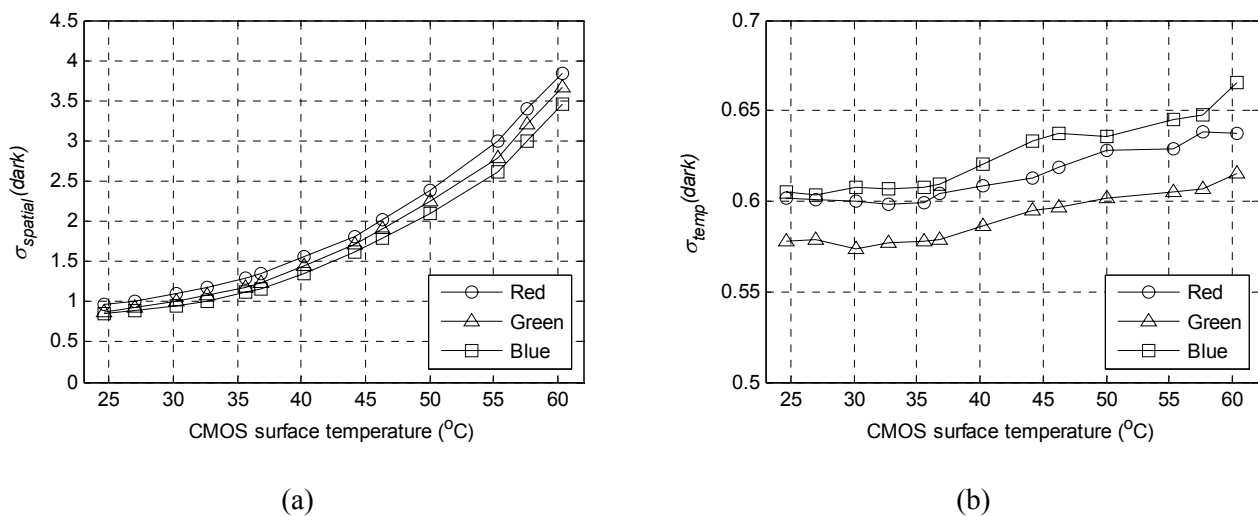
Fig. 2. CCD camera noise: spatial (a), temporal (b), total (c).

Table 2. Unibrain Fire i400 camera details.

Parameter	Value
Sensor type	Sony Wfine ICX098BQ 1/4" color CCD (Bayer colour filter)
Native resolution	640 x 480
Video mode	24-bit RGB (8-bits/channel)
Interface	IEEE-1394a (Firewire)

4.3. Temperature

Offset FPN, dark current shot noise, readout noise, and column noise all depend upon temperature. The effect of temperature was analyzed for the CMOS and CCD cameras by capturing image sets at various temperatures with zero illumination. The cameras were placed inside a thermally insulated enclosure with a controllable heat source, and the ambient temperature and surface sensor temperatures were allowed to stabilize for approximately 10 minutes before images were captured. The temperatures were measured using thermocouples, with the sensor thermocouple mounted on the front of the integrated circuit package of each camera. Measurements of spatial and temporal noise were made, with results shown in Figs. 3 and 4. The graphs show almost opposite responses between the CCD and CMOS cameras with CCD temporal noise significantly greater than spatial noise and vice versa for the CMOS camera. The cause of the dip in the temperature noise curves for the CCD camera is unknown, but the same effect was evident in three separate experiments.

**Fig. 3.** Spatial (a) and temporal (b) noise for varying CMOS surface temperature in dark conditions.

5. Discussion

Figs. 1 and 2 highlight significant differences in the relative and total magnitudes of the cameras' noise components. The spatial noise in the CMOS camera demonstrates a relatively large amount of offset FPN compared to the CCD, while the CCD camera demonstrates substantial amounts of PRNU as shown by the linearly increasing spatial noise. The channel responses of the CMOS camera exhibit similar noise magnitudes in all forms of noise, yet the CCD demonstrates higher noise in its red and blue channels. Apart from green values below approximately 50, the CMOS camera exhibits lower noise than the CCD camera in temporal and total noise value when operating in an ambient environment of approximately 22°C.

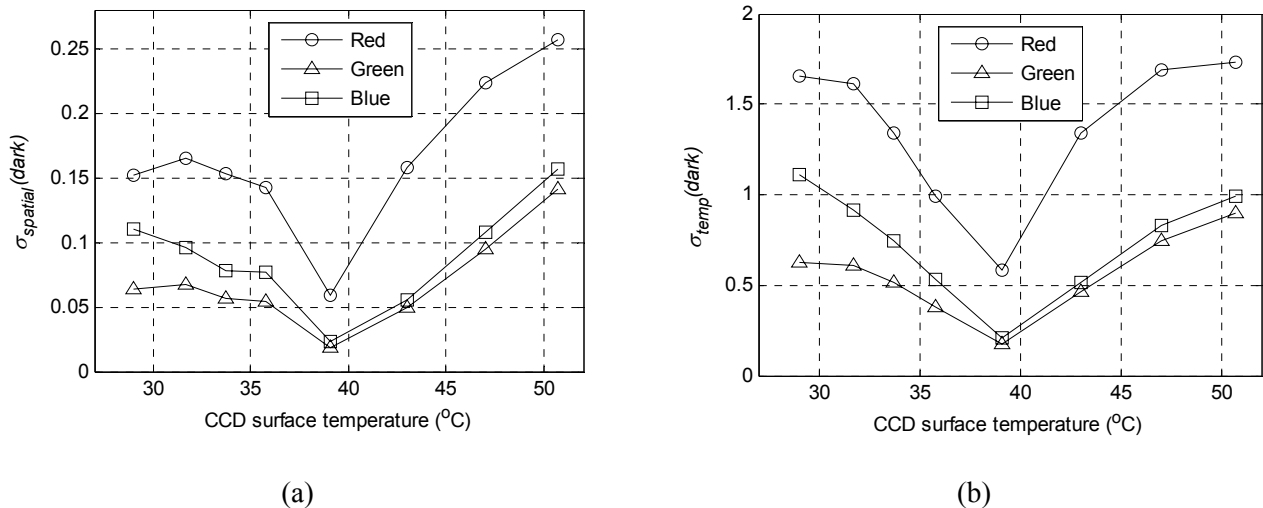


Fig. 4. Spatial (a) and temporal (b) noise for varying CCD surface temperature in dark conditions.

Experiments have shown that temperature can have a significant impact on image noise. The CMOS temperature response fits with the theory that camera noise increases with temperature, whereas the CCD response demonstrates an uncharacteristic response by showing a reduction on noise between 30° C and 40° C. It is clearly important to ensure that any noise analysis for the purpose of an image-processing application occurs at the environmental temperature that the camera will be operating in.

The results of this work have shown considerable differences in noise characteristics between the CCD and CMOS cameras analyzed. The quantity and quality of noise cannot be assumed to be consistent between cameras, and should be measured prior to any application incorporating noise values as parameters.

6. Conclusion

A method for measuring noise in cameras has been developed that can be used as an input into image processing applications. 100 images of a patch chart such as the GMB chart can provide the necessary information to measure the amount of spatial, temporal and total noise in a camera. The amount and shape of the noise response to illumination can vary significantly from camera to camera, and can have a high dependency upon the environmental temperature.

Acknowledgement

This work was supported by the New Zealand Foundation for Research, Science and Technology programme LVLX0401.

References

- [1]. J. Nakamura, Image Sensors and Signal Processing for Digital Still Cameras, *CRC Press*, 2006.
- [2]. R. E. Flory, Image acquisition technology, In *Proceedings of the IEEE*, Vol. 73, 1985, pp. 613-637.
- [3]. A. El Gamal and H. Eltoukhy, CMOS image sensors, *Circuits and Devices Magazine, IEEE*, Vol. 21, 2005, pp. 6-20.

- [4]. L. Brouk and Y. Nemirovsky, CMOS SOI image sensor, In *Proceedings of the IEEE International Conference on Electronics, Circuits and Systems*, Vol. 11, 2004, pp. 156-159.
- [5]. T. Anaxagoras, N. Guerrini, R. Turchetta, and N. M. Allinson, High Dynamic Range Sensor Active Pixel Sensor, In *Proceedings of the First International Conference on Sensing Technology*, 21-23 November 2005, pp. 448-453.
- [6]. R. Costantini and S. Süssstrunk, Virtual Sensor Design, In *Proceedings of SPIE Sensors and Camera Systems for Scientific, Industrial, and Digital Photography Applications V.*, 2004, Vol. 5301, pp. 408-419.
- [7]. T. Chen, P. B. Catrysse, A. El Gamal, and B. A. Wandell, How small should pixel size be?, In *Proceedings of SPIE Sensors and Camera Systems for Scientific, Industrial, and Digital Photography Applications*, Vol. 3965, 2000, pp. 451-459.
- [8]. P. B. Catrysse, M. Wang, and A. El Gamal, Comparative analysis of color architectures for image sensors, In *Proceedings of SPIE Sensors, Cameras, and Applications for Digital Photography*, Vol. 3650, March 1999, pp. 26-35.
- [9]. P. Horowitz and W. Hill, *The Art of Electronics*, Second ed. Melbourne, 1989.
- [10]. G. E. Healey and R. Kondepudy, Radiometric CCD camera calibration and noise estimation, *IEEE Trans. on Pattern Analysis and Machine Intelligence*, Vol. 16, 1994., pp. 267-276
- [11]. CCD Technology Primer, Dalsa Inc (www.dalsa.com).
- [12]. S. Baier, CCD Imaging Systems, Burr-Brown Corp.
- [13]. H. W. Ott, *Noise Reduction Techniques in Electronic Systems*, Second ed. Canada, 1988.
- [14]. B. K. Gunturk, J. Glotzbach, Y. Altunbasak, R. W. Schafer, and R. M. Mersereau, Demosaicking: Color Filter Array Interpolation (Exploring the imaging process and the correlations among three color planes in single-chip digital cameras), *IEEE Signal Processing*, Vol. 22, 2005, pp. 44-54.
- [15]. H. Baher, *Analog and digital signal processing*, John Wiley & Sons Ltd, 1990.
- [16]. K. Irie, A. E. McKinnon, K. Unsworth, and I. M. Woodhead, A comparison of noise in CCD and CMOS image sensors, In *Proc. Image and Vision Computing New Zealand Great Barrier Island*, New Zealand, 2006, pp. 43-48.
- [17]. G. K. Bhattacharyya and R. A. Johnson, *Statistical concepts and methods*, John Wiley & Sons, Inc., 1977.

2008 Copyright ©, International Frequency Sensor Association (IFSA). All rights reserved.
(<http://www.sensorsportal.com>)

Sensors & Transducers Journal 2007 on CD



156.504

2007 e-Impact Factor

ISSN 1726-5479

12 Issues, 75-86 Volumes
+ Special Issue

Order online:

http://www.sensorsportal.com/HTML/DIGEST/Journal_CD_2007.htm

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 addition, 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/Submission.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



**e-Impact Factor 2007:
156.504**



Subscription 2008

*Sensors & Transducers Journal (ISSN 1726-5479)
for scientists and engineers who need to be
at cutting-edge of sensor and measuring
technologies and their applications.*

*Keep up-to-date with the latest, most significant
advances in all areas of sensors and transducers.*

**Take an advantage of IFSA membership
and save **40 %** of subscription cost.**

Subscribe online:

http://www.sensorsportal.com/HTML/DIGEST/Journal_Subscription_2008.htm

www.sensorsportal.com