

ISSN 1726-5479

# SENSORS & TRANSDUCERS

9<sup>vol. 120</sup>  
/10



## TEDS Sensors, IEEE 1451 Standards

International Frequency Sensor Association Publishing





**Editors-in-Chief:** professor Sergey Y. Yurish, tel.: +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, Università 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**, Northern 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**, N.I. Center for Higher Education, (N.I. University), 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  
**Diegues, Angel**, University of Barcelona, Spain  
**Dimitropoulos, Panos**, University of Thessaly, Greece  
**Ding, Jianning**, Jiangsu Polytechnic University, China  
**Kim, Min Young**, Kyungpook National University, Korea South

**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 Alcalá, 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  
**Saxena, Vibha**, Bhabha Atomic Research Centre, Mumbai, India

**Ko, Sang Choon**, Electronics. and Telecom. Research Inst., 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**, University of Vigo, Spain  
**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  
**Raof, 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  
**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  
**Shah, Kriyang**, La Trobe University, Australia  
**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  
**Soleymannpour, 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  
**Vanga, Raghav Rao**, Summit Technology Services, Inc., USA  
**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**, Pacific Northwest National Laboratory, 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  
**Zakaria, Zulkarnay**, University Malaysia Perlis, Malaysia  
**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, Quintao**, 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

# Contents

Volume 120  
Issue 9  
September 2010

www.sensorsportal.com

ISSN 1726-5479

## Research Articles

<b>Design of a Modular Signal Conditioning Circuit for Biopotential Sensors</b> <i>Winncy Y. Du, Winston Jose, Jake Askeland</i> .....	1
<b>MEMS Accelerometers Sensors: an Application in Virtual Reality</b> <i>Daniel Corrêa, Douglas Santos, Leonardo Contini, Alexandre Balbinot</i> .....	13
<b>Contactless Quality Monitoring Sensor Based on Electrical Conductivity Measurements</b> <i>Armin Satz, W. Granig, D. Tumpold and F. Reininger</i> .....	27
<b>Gas Sensing Properties of Pure and Cr Activated WO<sub>3</sub> Thick Film Resistors</b> <i>V. B. Gaikwad, R. L. Patil, M. K. Deore, R. M. Chaudhari, P. D. Hire, S. D. Shinde, G. H. Jain</i> .....	38
<b>Ellipsometric Immunosensor for Detection of Amyloid Precursor Protein with a View of Alzheimer's Disease Diagnostics</b> <i>Alexei Nabok, Mohd Kamarulzaki Mustafa, David Parkinson, Anna Tsargorodskaya</i> .....	53
<b>Optical Tomography System: Charge-coupled Device Linear Image Sensors</b> <i>M. Idroas, R. Abdul Rahim, M. H. Fazalul Rahiman, R. G. Green, M. N. Ibrahim</i> .....	62
<b>Spray Pyrolyzed Polycrystalline Tin Oxide Thin Film as Hydrogen Sensor</b> <i>Ganesh E. Patil, D. D. Kajale, D. N. Chavan, N.K. Pawar, V. B. Gaikwad, G. H. Jain</i> .....	70
<b>Research of a Novel Three-dimensional Force Flexible Tactile Sensor Based on Conductive Rubber</b> <i>Fei Xu, Yunjian Ge</i> .....	80
<b>Induction Magnetometers – Design Peculiarities</b> <i>Valeriy Korepanov, Vira Pronenko</i> .....	92
<b>Noise Feature Analysis in Pulse Temperature Modulated MOS Gas Sensors</b> <i>Nimisha Dutta and Manabendra Bhuyan</i> .....	107
<b>Drowsy Driver Detection via Steering Wheel</b> <i>Herlina Abdul Rahim, Zulkifli Yusop and Ruzairi Abdul Rahim</i> .....	119
<b>Microwave Detection of Soil Moisture Using C-Band Rectangular Waveguide</b> <i>Jayesh Pabari, Shrutisingh Yadav and Rajani Singh</i> .....	134
<b>Performance Characterization of a Long-Stroke Direct-Drive Electromagnetic Linear Actuator</b> <i>Mohammad I. Kilani</i> .....	142
<b>Sensitivity Enhancement of Biochemical Sensors Based on Er<sup>+3</sup> Doped Microsphere Coupled to an External Mirror</b> <i>Alireza Bahrampour, Azam Gholampour Azhir, Razie Taghiabadi, Kazem Rahimi Yazdi</i> .....	152

**Design and Development of Embedded Based System for the Measurement of Dielectric Constant Spectroscopy for Liquids**

V. V. Ramana C. H., Narsinga Rao S., Ashok Kumar M., Jayaramudu J., Kathalingam A., Sudhakar S., Mi-Ra Kim, Yeon- Sik Chae and Jin-Koo Rhee..... 162

**Implementation of Distributed Measurement Process on Clinical Blood Analyzer**

P. Neelamegam, S. Kumaravel, K. Muruganathan ..... 171

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

International Frequency Sensor Association (IFSA).

**IMU Market 2007-2012**  
Yole's IMU market report  
**IFSA offers a SPECIAL PRICE**

**Competitive market analysis of the RLG – FOG – DTG - Quartz and MEMS based Inertial Measurement Units**

*This report not only describes the market at the player and application level, but it provides a global view of the IMU market allowing the report user to build diversification strategies taking into account technical requirements.*

[http://www.sensorsportal.com/HTML/IMU\\_Markets.htm](http://www.sensorsportal.com/HTML/IMU_Markets.htm)



**Emerging MEMS 2010**  
Technologies & Markets 2010 Report

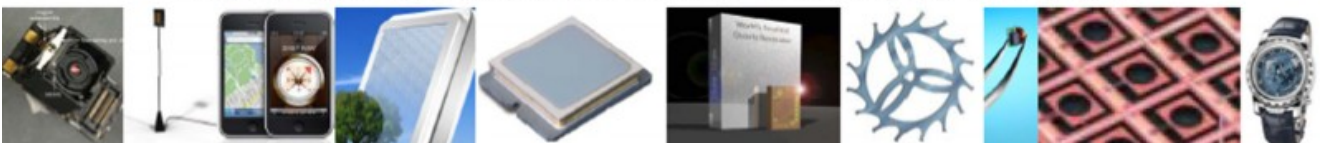
**Innovative developments in MEMS devices will add more than \$2B to the total MEMS market by 2015 !**

*This report presents a market and technical overview for MEMS-based Auto Focus, Electronic Compass, Energy Harvesting, Micro-bolometers, Micro displays, Micro fuel cells, Micro speakers, Micro structures, Microtips, Oscillators and RFID.*

*Estimated to be \$550M in 2009 a few % of the total MEMS business, Emerging MEMS markets have the potential to add \$2.2B to the overall MEMS market by 2015.*

**IFSA offers a SPECIAL PRICE**

[http://www.sensorsportal.com/HTML/Emerging\\_MEMS.htm](http://www.sensorsportal.com/HTML/Emerging_MEMS.htm)



## The Sixth International Conference on Systems



# ICONS 2011

January 23-28, 2011 - St. Maarten,  
The Netherlands Antilles



### Important deadlines:

Submission (full paper)	September 25, 2010
Notification	October 20, 2010
Registration	November 5, 2010
Camera ready	November 5, 2010

<http://www.iaria.org/conferences2011/ICONS11.html>

### Tracks:

- Systems' theory and practice
- System engineering
- System instrumentation
- Embedded systems and systems-on-the-chip
- Target-oriented systems [emulation, simulation, prediction, etc.]
- Specialized systems [sensor-based, mobile, multimedia, biometrics, etc.]
- Validation systems
- Security and protection systems
- Advanced systems [expert, tutoring, self-adapting, interactive, etc.]
- Application-oriented systems [content, eHealth, radar, financial, vehicular, etc.]
- Safety in industrial systems
- Complex Systems

## The Seventh International Conference on Networking and Services



# ICNS 2011

May 22-27, 2011 - Venice, Italy



### Important deadlines:

Submission (full paper)	January 10, 2011
Notification	February 20, 2011
Registration	March 5, 2011
Camera ready	March 20, 2011

<http://www.iaria.org/conferences2011/ICNS11.html>

### Tracks:

- ENCOT: Emerging Network Communications and Technologies
- COMAN: Network Control and Management
- SERVI: Multi-technology service deployment and assurance
- NGNUS: Next Generation Networks and Ubiquitous Services
- MPQSI: Multi Provider QoS/SLA Internetworking
- GRIDNS: Grid Networks and Services
- EDNA: Emergency Services and Disaster Recovery of Networks and Applications
- IPv6DFI: Deploying the Future Infrastructure
- IPDy: Internet Packet Dynamics
- GOBS: GRID over Optical Burst Switching Networks

## The Third International Conference on Bioinformatics, Biocomputational Systems and Biotechnologies



# BIOTECHNO 2011

May 22-27, 2011 - Venice, Italy



### Tracks:

#### A. Bioinformatics, chemoinformatics, neuroinformatics and applications

- Bioinformatics
- Advanced biocomputation technologies
- Chemoinformatics
- Bioimaging
- Neuroinformatics

#### B. Computational systems

- Bio-ontologies and semantics
- Biocomputing
- Genetics
- Molecular and Cellular Biology
- Microbiology

#### C. Biotechnologies and biomanufacturing

- Fundamentals in biotechnologies
- Biodevices
- Biomedical technologies
- Biological technologies
- Biomanufacturing

### Important deadlines:

Submission (full paper)	January 10, 2011
Notification	February 20, 2011
Registration	March 5, 2011
Camera ready	March 20, 2011

<http://www.iaria.org/conferences2011/BIOTECHNO11.html>

## Induction Magnetometers – Design Peculiarities

Valeriy KOREPANOV, Vira PRONENKO

Lviv Centre of Institute for Space Research, 5-A Naukova str., Lviv, 79060, Ukraine

Tel.: +380 32 2639163

E-mail: [lessia1@isr.lviv.ua](mailto:lessia1@isr.lviv.ua)

*Received: 26 August 2010 / Accepted: 14 September 2010 / Published: 27 September 2010*

---

**Abstract:** Induction or search-coil magnetometers (IM) are widely used in many branches of science and industry. The frequency range and dynamic range of IMs are probably the widest of all existing magnetometers: they are used for the measurement of magnetic field variations in the frequency band from  $\sim 10^{-4}$  till  $\sim 10^6$  Hz with the intensities from fractions of femtotesla till tens of tesla. This explains the permanent interest to IM design and the attempts to construct the IMs with best possible parameters. The present paper deals with the peculiarities of IM design. An attempt to re-establish the correctness of priorities in the field is made and the approaches to the IM optimization and their quality estimation are described. *Copyright © 2010 IFSA.*

**Keywords:** AC magnetic field, Induction magnetometer, Design, Quality factor.

---

### 1. Introduction

Induction or search-coil magnetometers (IM) are widely used for the experimental study of natural and man-made magnetic fields variations in the frequency band from  $\sim 10^{-4}$  till  $\sim 10^6$  Hz for science and engineering application in land and space conditions. They are probably the most widespread devices used for the magnetic field study. Certainly, different application areas impose different requirements to the main IM parameters. For example, field geophysics needs as low as possible magnetic noise level (NL) of IM and such parameters as length, weight and power consumption have secondary importance. Space research, to as low as possible NL requirement, needs weight and power consumption minimization. And some special types of application require very small IM dimensions and power consumption, still requiring as low as possible NL. This shows that, independently on other requirements, to get as low as possible NL remains the most important demand and at close or equal figures for other parameters the NL may be used to compare the IM quality.

Despite IMs are used probably more than a couple of centuries, the interest to them and to their design peculiarities is still at enough high level, what is proved by a good number of publications in recent few years. There are several reasons which induced the authors to write still one paper devoted to the IM design.

First, this is a desire to re-establish the correctness of the priorities in the field. Unfortunately, Cyrillic alphabet and “iron curtain” caused that the considerable theoretical and experimental groundwork made in Former Soviet Union still remains unknown to the international scientific community. For example, Russian scientist V. Arkadyev was probably the first who showed theoretically and experimentally the role of demagnetization factor for metallic rods [1], whereas the earliest cited work in this field in western papers is attributed to R. Bozorth and D. Chapin [2], which was published 7 years later. The detailed study of the demagnetization factor was executed in a fundamental work of M. Rozenblat [3] published the same year as the paper of K. Warmuth [4], though the first author was never cited by Western authors. And the best known monograph about IM design of Prof. L. Miziuk [5] published in 1964 is not known to the western experts at all, though a great deal of expressions given there are listed again by later authors as original ones.

Next is the desire to put right accents in the development problem of IM. The best found western paper devoted to IM design [6] pays much attention to the sensor (coil and core) design and very little attention is paid to the main problem in the field – *noise matching* of the sensor and amplifier, whereas this is a principle question to get low noise IM [5, 7]. In later publications [8, 9] this problem is omitted completely, as well as in the recent ones, where the necessary probably too complicated calculations are substituted by “intuitive” decision [10] or by very peculiar understanding of what the IM optimization means [11]. We want to stress that, if your goal is to create the IM with lowest possible NL, it is a wrong way to calculate first the sensor parameters and then to find an amplifier to it. Only a complex optimization of sensor-amplifier system according to the selected criterion – weight or length – can give really optimal IM construction with lowest possible NL in the given frequency range [12].

The ways to get low NL when designing IM are shortly outlined below and the attempt to compare the known IM quality is made.

## **2. IM operation Principle**

The IM transfer function may be derived from the Faraday law of induction:

$$u = -n \cdot \frac{d\Phi}{dt},$$

where  $u$  is the voltage induced in a coil which has  $n$  turns,  $\Phi$  is magnetic flux. In the case of a sinusoidal flux variation directed along a longitudinal axis of the core  $\Phi = \Phi_{\max} \cdot \cos(\omega t)$ , where  $\omega$  is circular frequency.

Taking this into account, the open-loop peak output voltage of the coil wound on the high-permeability core may be presented as follows:

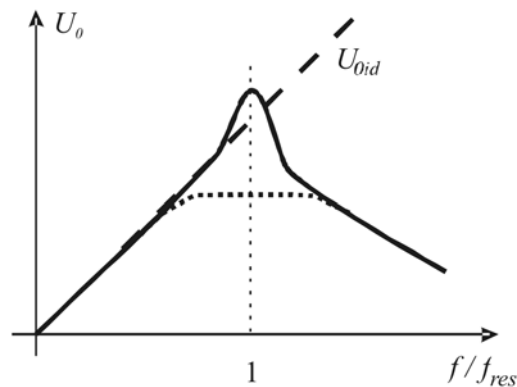
$$U_0 = \omega \cdot n \cdot \Phi_{\max} = \omega \cdot n \cdot S \cdot \mu_0 \cdot \mu_c \cdot H_e = G \cdot H_e, \quad (1)$$



where  $\mu_0$  is permeability constant,  $\mu_c$  is relative permeability of the core,  $S$  is cross section of the core,  $H_e$  is measured external magnetic field peak intensity,  $G$  is IM sensitivity.

According to (1), ideally, the coil output signal has to depend linearly on frequency ( $U_{0id}$  on Fig. 1). But due to the sensor winding equivalent resistance  $R_e$ , inductance  $L$  and capacitance  $C$  the dependence  $U_0 = f(\omega)$  or  $U_0(f)$  is more complicated. Inductance  $L$  and capacitance  $C$  form the resonance circuit the Q-factor of which depends on the resistance  $R_e$  and typical frequency characteristic of an induction coil is presented on Fig. 1 by the solid line. So, we see from this figure that expression (1) is valid only for the frequency band lower than the resonance frequency.

IM may be used in a resonance mode with transfer function as shown by solid line on Fig. 1 for the measurement of the magnetic field fluctuations if the frequency range of interest is very narrow or in time domain mode at frequencies lower than resonance frequency. But in case of the measured signal with wide complex spectra it is necessary to have a wide-band induction magnetometer with linear-flat frequency response (see Fig. 1, dotted line). It can be obtained by several ways: 1) output signal integration, 2) using the sensor with current amplifier, 3) using the sensor with transformer coupled negative feedback.



**Fig. 1.** Solid line – amplitude-frequency response of an induction coil output peak voltage  $U_0$  in resonance mode ( $f_{res}$  is a resonance frequency); dashed line – ideal shape of this response; dotted line – typical frequency response of IM.

Each of these operation modes has their own design peculiarities.

1. As it is seen from expression (1) and Fig. 1, the induction coil works as differential section at frequencies lower than resonance frequency. Integration of output signal may make the response linear. In this case IM frequency range is limited at high frequencies by resonance frequency, at low frequencies - by integrator zero drift.
2. In the case of coupling the coil with a current amplifier the coil is loaded by inverting operation amplifier, so it will operate close to short-circuit mode. Frequency response will be linear up to frequency  $\omega_1 = R/L$ , after that it will be independent on the frequency. The main drawbacks of this circuit are difficulty of its realization at low frequency and higher sensitivity threshold than in the circuit with voltage amplifier.
3. Sensor with transformer coupled negative feedback by the magnetic flux allows obtaining wide-band frequency response, low sensitivity threshold and the main feature of this version is the

possibility to control the flat part of amplitude-frequency response in wide range, up to very low frequencies. So, it is evident that the last solution is the most widespread in practice.

Let us consider the peculiarities of low-noise IM design.

### **3. Core and Winding Influence on IM Parameters**

If to analyze expression (1), it may be seen that the IM output signal is proportional to the winding turns number  $n$ , core cross-section  $S$  and core permeability  $\mu_c$ . We may conclude that to increase IM sensitivity we have to make every of these values as big as possible. Let us see first what is resulting with  $\mu_c$  increase.

First step to get high  $\mu_c$  is to use the soft magnetic material with as high as possible relative permeability  $\mu$ . But because of the demagnetizing field effect [1] the resultant core permeability  $\mu_c$  is lower than permeability of core material  $\mu$  and strongly depends on the core shape. It can be calculated as [5]:

$$\mu_c = \frac{\mu}{1 + N(\mu - 1)}, \quad (2)$$

where  $N$  is the demagnetizing factor. The demagnetizing factor  $N$  is geometry dependent and, slightly modifying the corresponding expression in [5], we may consider that its value is determined by the ratio  $m$  of the core length  $l$  and diameter  $d$ :

$$N \approx \frac{\ln 2m - 1}{m^2}, \quad (3)$$

It is known that the material permeability  $\mu$  may change considerably with time and temperature and here  $N$  plays an important role for the stabilization of the factor  $\mu_c$  in the expression (1).

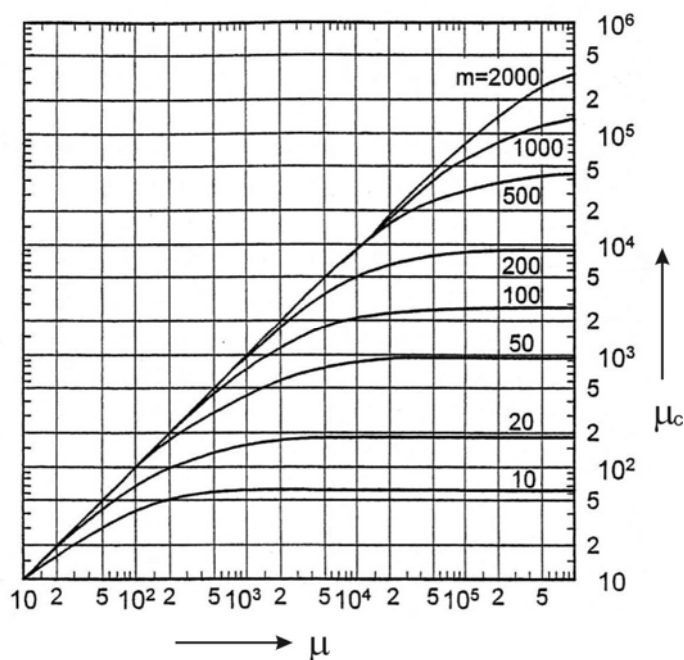
It is necessary to mention that the demagnetizing factor  $N$  according to the expression (3) in reality is valid only for three-axes rotational ellipsoids. N. Feldkeller proposed the simplified expression

$$N = 5S / l^2, \quad (4)$$

which gives enough low error and is widely used for practical calculations [13].

Fig. 2 allows determining lowest acceptable limit of  $\mu$  at given ratio  $m$  in order to keep  $\mu_c$  constant in wide limits of possible  $\mu$  changes under the influence of different factors.

As we already stated, the more is  $\mu_c$ , the higher is IM sensitivity, so elongated wire-like core construction with  $m > 50$  is recommended. But as it is seen from Fig. 2, for this case it is necessary to select material with  $\mu > 30000$ , otherwise its changes may lead to the sensitivity variations, what is not desirable.



**Fig. 2.** Core permeability  $\mu_c$  of cylindrical rods versus the material permeability  $\mu$  with length-to-diameter ratio  $m$  of the rod as a parameter, after [2].

It is necessary also to take into account that the existence of a permanent Earth's magnetic field may lead to the core magnetization and core material saturation with corresponding sharp degradation of  $G$  and other IM parameters. So, for strongly elongated cores the maximal admissible  $\mu_{c\max}$  value has to be estimated in order the sensitivity variations in the outer filled  $H_e \leq H_{\max}$  were below admissible relative error  $\delta$ . The approximate expression [14] gives:

$$\mu_{c\max} = \frac{\mu}{\sqrt[3]{\left(\frac{1}{\delta} - 1\right) \left(\frac{\pi H_{\max} \mu}{2B_s}\right)^2 - 1}}, \quad (5)$$

where  $B_s$  is the saturation induction of the core material.

This equation is valid approximately until  $\mu_c H_e < B_s$ . The calculations show that  $\delta$  value changes very sharply when  $\mu_c$  approaches to:

$$\mu_{c\max} = B_s H_e^{-1}.$$

That is why the value of  $\mu_{c\max}$  determined from the equation (5) with the guaranteed margin is the obligatory upper restriction in order to avoid large errors because of the IM core magnetization in the permanent outer field.

So, at recommended  $m$  values (50-100), high  $\mu$  (larger than 50000) allows obtaining  $\mu_c$  up to 2500 with enough low sensitivity to  $\mu$  variations (see Fig. 2). Also the moderate value of  $\mu_c$  guarantees that core will not be magnetized in the Earth's permanent magnetic field.

Considering the core dimensions, let us remind that the core cross-section area  $S$  itself also is directly connected with output voltage value – see (1). But, as we showed above, the relation  $m = l/d$  is already determined from other considerations and to increase  $S$  or, what is the same,  $d$ , will reduce proportionally  $m$ , then  $\mu_c$  will decrease too and reduce the effect of  $S$  increment. Recently several successful attempts were made to overcome this restriction: the so called flux concentrators are added to both ends of the core, so augmenting  $S$  without considerable deterioration of  $m$  [10, 11]. It is reported about “threefold” increasing of the IM sensitivity with the ratio of flux concentrator diameter  $D_c$  and core diameter  $d \approx 5$  [11]. In cited works the sensitivity increment is attributed to the increase of  $\mu_c$ , named there “apparent permeability”, but this postulate is not substantiated, neither theoretically nor experimentally. The reported there mathematical model of the effect of magnetic flux concentration in reality refers not to  $\mu_c$  increase, but to the increase of the efficient surface  $S$  of the core tips. This difference has principal character: if flux concentrators increase  $\mu_c$ , then they spoil accordingly to Fig. 2 the  $\mu_c$  stability in time and temperature; if only  $S$  is increasing, then no negative effect at all.

Last possibility to raise the IM sensitivity- to increase the winding turns number  $n$ , according to expression (1), – is also not so efficient because augmenting  $n$  leads to the increase of the winding active resistance  $R$  and thermal noise correspondingly. So, it is necessary to increase the copper wire diameter simultaneously, what leads to the copper weight  $M$  increase. The theoretical and experimental studies show, that the IM sensitivity threshold  $W_{BM}$  depends on the winding (copper) weight  $M$  as follows [7]:

$$W_{BM} = \frac{K}{\mu_c \cdot \omega \cdot d \cdot \sqrt{M}}, \quad (6)$$

where  $K = 8 \cdot \sqrt{k \cdot T \cdot \Delta f \cdot \rho \cdot \gamma}$ . So, IM sensitivity depends mainly on copper weight  $M$  and the turns number is selected mostly for the optimal matching of the coil and preamplifier, what relates to the optimization problem of IM design discussed further.

Before to proceed with the IM optimization, let us make still one objection as to the winding influence on IM sensitivity. It is evident that in majority of IM constructions the coil is not wound on the core itself – a special reel is used. So, the coil wound on the reel has internal  $D_i$  and external  $D_e$  diameters and following relation is valid:  $D_e > D_i > d$ .

It is also known that the greater is this inequality, the lower is IM sensitivity  $G$  [7]. So, we may state that  $G$  is inversely proportional to coil mean diameter  $D_m = \frac{D_e + D_i}{2}$ . Simple physical considerations allow us to ascertain this to the efficient value of  $\mu_c$  reduction, if a system “core-coil” is considered:  $\mu_c \equiv D_m^{-3/2}$  [7].

Further  $\mu_c$  reduction is caused because IM manufacturers select the coil length  $l_n$  always smaller than the core length  $l$ . This is because  $\mu_c$  is not uniform along the core and its maximal value  $\mu_{cc}$ , which is located in the center, for a commonly used prismatic rods is given by the expression [5]:

$$\mu_{cc} = \frac{\mu}{1 + 0.974 \frac{S}{l^2} \left[ \ln \left( l \cdot \sqrt{\frac{\pi}{S}} \right) - 1 \right] \cdot (\mu - 1)}. \quad (7)$$

The coil length  $l_n$  occupies not all the core length  $l$  because the relative voltage picked up by the coil is decreasing with  $l_n/l \rightarrow 1$  [6]. In general case the following relation is recommended:

$$l_n \approx (0.5 - 0.7)l. \quad (8)$$

From this point of view to name “optimal” the coil construction, which covers all the core length, proposed in [11] is rather doubtful.

Correspondingly, average value  $\mu_{cca}$  of the  $\mu_c$ , which has to be taken into account for the coil with fixed  $l_n$  gives [5]:

$$\mu_{cca} = \mu_{cc} \cdot \left[ 1 - 0.255 \cdot \left( \frac{l_n}{l} \right)^2 \right]. \quad (9)$$

After the influence of main coil and core parameters on the IM sensitivity are considered, let us discuss the peculiarities of IM optimal design.

#### **4. IM Design Methodology**

For relatively narrow-band IM ( $f_{\max}/f_{\min} < 1000$ ) it is not very difficult to determine the sensor parameters and the simple approach given in [10, 11] will not give big error: really achievable noise level is close to the theoretical one for given weight and dimensions of a sensor.

For wide-band IM ( $f_{\max}/f_{\min} > 1000$ ) direct optimal matching of sensor and preamplifier is impossible because of different dependence of sensor output impedance and optimal impedance of signal source for the preamplifier on frequency. Calculation of IM noise with given threshold sensitivity for wide frequency band and weight/dimensions restrictions requires taking into account simultaneously a great number of its parameters (for sensor only more than 30 geometric and electric values are described in the known papers). To this some of these parameters are mutually dependent or can be chosen from the restricted range (e.g., wire diameter). That is why in spite of as one would think rather simple task, the optimal set of values determination by versions look-over or equations system solution is impossible.

To make the task easier, two possibilities are used in practice:

- 1) The intermediate parameters of sensor and preamplifier which are necessary for calculations are chosen on the base of precedent tests of similar devices and then noise parameters are calculated for a number of sets of possible values given by the desired construction;
- 2) The recommended in papers relations between some intermediate parameters are accepted and another ones which are necessary for calculations are postulated, proceeding from general considerations.

In the first case the look-over of the versions doesn't guarantee the optimum set achievement at any rate, first of all because the selection of versions is executed arbitrarily. In the second one the parameters partly are selected also arbitrarily and the use of known equations without taking into account corresponding limitations, within which they were deduced, can give considerable errors.

Mostly the optimal combination of sensor and preamplifier one finds as a calculation of optimal sensor parameters for an ideal preamplifier, and then the matching with the real preamplifier is executed by the sensor turns number correction. This procedure gives not absolute optimum combination but the

complex of two relative optima, what leads to incorrect result, especially important in high frequency band.

A new approach for the optimized wide-band IM design was proposed [13, 14] and corresponding calculation method and computer program were developed. The main peculiarity of this method consists in the introduction of so called “generalized parameters” of the sensor, which values may be considered as constant for the given core material.

A set of 4 main generalized parameters  $K_i$  and 3 additional ones are given in the Table 1.

**Table 1.** IM generalized parameters.

Parameter	Dimensionality	Physical sense	Tentative estimation
$K_S$	V/(T·Hz · m <sup>2</sup> · turn)	Open-circuit sensitivity of sensor with 1 m length and one turn winding at 1 Hz	1 ± 20 %
$K_L$	H/(m·turn <sup>2</sup> )	Inductance of the same sensor	2·10 <sup>-7</sup> ± 25 %
$K_f$	Hz/(m <sup>1/2</sup> · turn)	Own resonance frequency of the same sensor	4·10 <sup>7</sup> ± 25 %
$K_R$	Hz· m <sup>2</sup>	Frequency, for which inductive and active resistances are equal for the same sensor	0.5 ÷ 3.5
$f_F$	Hz	Frequency, for which sensor Q-factor determined by eddy currents in the core, is equal to 1	(5 ÷ 500)·10 <sup>3</sup>
$Q_h$	-	Q-factor, determined by hysteresis losses in the core	50 ÷ 200
$Q_0$	-	Q-factor at the resonance frequency, determined by losses in parasitic capacitances	3 ÷ 10

It is obvious that the dispersion of parameters  $K_R, f_F, Q_h$  and  $Q_0$  are enough wide. But these parameters have relatively weak influence on the IM total noise level and only upon separate parts of the frequency band.

The use of generalized parameters allows conceiving all the sensor parameters in very simple and physically clear form, for example:

$$G = K_S f \cdot l^2 \cdot n ; \quad (10)$$

$$L = K_L \cdot l \cdot n^2 ; \quad (11)$$

$$Q = 1/[K_R/(f \cdot l^2) + 1/Q_h + f/f_F] ; \quad (12)$$

$$f_{res} = K_f/(l^{1/2} \cdot n) ; \quad (13)$$

$$R = 2\pi K_R \cdot K_L \cdot w^2 / l , \quad (14)$$

where  $Q$  is the main component of q-factor, depends on core and winding losses.

As a comment, it is necessary to say the following. The choice of a determined combination of generalized parameters means implicitly the choice of IM materials and construction with determined geometrical sizes relation. That is why the given calculation methodology is especially simple and efficient for the determination of optimal length and turns number of geometrically similar IM for standard operation conditions (wide frequency band, including infralow part, limited weight etc.).

As to a preamplifier, the frequency spectrum of its noise is characterized by an extended set of 8 noise parameters: minimal noise voltage density  $W_{u0}$ ; corner frequency and angle of elevation at low frequencies  $f_{u1}$ ,  $\alpha_u$ ; corner frequency of additional elevation at extremely low frequencies  $f_{u2}$ ; minimal noise current density  $W_{i0}$ ; corner frequency and elevation angle of the current noise at high frequencies  $f_{i1}$ ,  $\alpha_i$ ; corner frequency at low frequencies  $f_{i2}$ . Then voltage and current noise densities frequency responses of the amplifier may be calculated with the equations:

$$W_{uamp} = W_{u0} [1 + (f / f_{u1})^{\alpha_u} + (f / f_{u2})^2]; \quad (15)$$

$$W_{iamp} = W_{i0} [1 + (f / f_{i1})^{\alpha_i} + (f_{i2} / f)^2]. \quad (16)$$

The equations for the calculation of frequency spectrum of the complete IM noise are composed according to equivalent IM diagram on Fig. 3, where  $E_x$  - output e.m.f. of the sensor,  $U_r$  - equivalent noise voltage of the active part of the sensor impedance (active resistance -  $R$ , hysteresis one -  $R_h$  and eddy currents losses one -  $R_F$ ) with density  $W_r = 4kT(R + R_h + R_F)$ ,  $I_{r0}$  - noise current of the losses ( $R_0$ ) in the output winding capacitance  $C$  with density  $W_{I_{r0}}$ ,  $R_i$  - input resistance of preamplifier (all resistors are supposed to be noiseless),  $U_n$  and  $I_n$  - input noise voltage and current of the preamplifier with densities  $W_{uamp}$  and  $W_{iamp}$  respectively, which are characterized by mentioned 8 parameters.

According to Fig. 3, the resulting voltage noise density  $W$  reduced to the amplifier input is:

$$W = W_r \cdot k_U^2 + W_{uamp} + (W_{iamp} + W_{I_{r0}}) \cdot Z^2 \cdot k_U^2, \quad (17)$$

$k_U = \frac{Z_C}{Z_C + Z_L}$  is the circuit transfer function, where  $Z = \frac{Z_C \cdot Z_L}{Z_C + Z_L}$  is the coil impedance,

$$Z_C = \frac{R_0 / j\omega C}{R_0 + 1 / j\omega C}, \quad Z_L = R + R_h + R_F + j\omega L.$$

The total power noise density in the values of the measured magnetic field  $W_B$ , using the definition for the coil sensitivity  $G = U_0 / H_e$  from (1), is

$$W_B = \frac{W}{G^2 \cdot k_U^2} = \frac{1}{G^2} \cdot \left[ W_r + \frac{W_{uamp}}{k_U^2} + (W_{iamp} + W_{I_{r0}}) \cdot Z^2 \right]. \quad (18)$$

On the base of the resulting expression (18) the calculation program was created with a developed service part, what allows us to present the set of IM NL in the form of plots or tables, where some given parameters can be changed, starting from those of sensor and ideal lossless preamplifier until the versions which are easy to make by simple technical means. By this procedure it is easy to find the parameters, which influence most significantly the noise in the given part of the frequency band. Service part of the program includes a set of values of generalized sensor parameters for a wide range of core materials and core constructions; also a number of input parameters for the different types of

preamplifiers are stored. A special version of the program is developed which allows automatic look-over of possible IM realizations within given limitations and alleviates the choice of the version, providing the minimum NL in the given frequency range.

When all main parameters of the sensor and the preamplifier are taken into account, high precision of final calculation results is guaranteed. Important is, that when given constructive parameters of the sensor are changed, the correction of corresponding changes in noise spectrum is made automatically. The example is given on Fig. 4 which illustrates the calculation example when sensor winding turns number is varied. It is clearly seen that the low frequency parts of noise plots are bent and noise minima are shifted to lower frequencies with the number of turns increasing (plots 1, 2, 3;  $w_3 > w_2 > w_1$ ). When an optimum is passed, IM noise becomes higher for all frequencies (plot 4,  $w_4 > w_3$ ).

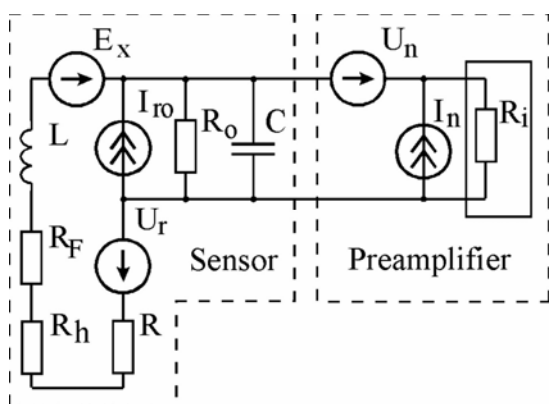


Fig. 3. Equivalent noise circuit of IM.

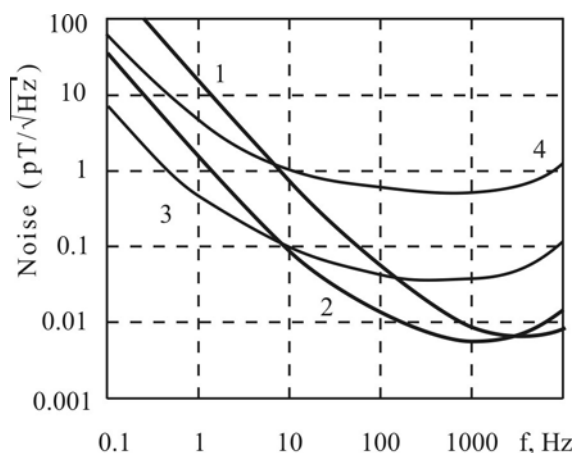


Fig. 4. Influence of turns number change on IM noise level.

To estimate how close the obtained magnetic noise density is to the lowest possible NL for the given length  $l$ , a following semi-empirical formula [15] may be used which gives theoretically lowest possible NL:

$$W_{Bl} \approx h_0(1 + A/l^5 \cdot f^2 + B/l^5 \cdot f^4)^{1/2}, \quad (19)$$

where  $h \approx 10^{-14} \text{T} / \text{Hz}^{1/2}$ ;  $A \approx 30 \text{ m}^5 \cdot \text{Hz}^2$ ;  $B \approx 10^{-4} \text{ m}^5 \cdot \text{Hz}^4$ .

Some comments to this expression are necessary. First, here it is postulated that the NL threshold is depending on  $l$  only, what is valid for geometrically similar IMs. Next, it has sense for the frequency band  $f < f_{res}$  only and is valid for the optimized IM with the core made of best materials with high  $\mu$ . And last, the second term  $- B/l^5 f^4$  – reflects the additional preamplifier noise increment in the infra-low frequency band for a direct amplification chip. If a chopper is used as a preamplifier, this term has to be neglected.

The restricted article volume does not allow us to go further into low noise IM design details which may be found in given references [5, 6, 7, 12, 15], but it is necessary to mention that, because of clear commercial validity of the optimal IM design to compete at world market, the most important details



of low noise IM manufacturing remain as know-hows of the producers, never published in open literature.

To compare the quality of the existing at the market IMs produced by different companies, an attempt to introduce an impartial assessment is made.

## 5. IM Quality Assessment

The principal goal to give the criteria to compare IM quality was to introduce a parameter which could help first of all to the numerous professional and amateur designers to estimate the efficiency of the novelties they introduce against the existing IM.

We realize that this task is not a simple one, as well as every IM has its individual parameters, operation frequency range etc. Nevertheless, taking into account the fundamental dependencies of the most important IM parameter – noise level – on sensor geometry and weight, we made an attempt to express it in terms of the postulates given in the present paper. Main of them are:

- NL threshold decreases with  $l$  as  $l^{5/2}$ ;
- NL threshold decreases with weight  $M$  as  $M^{1/2}$ .

For existing IM the  $W_B$  values of threshold NL for a fixed frequency are documented in technical specifications. Then a quality factor  $QF$  may be deduced as:

$$QF = \frac{K_c}{W_B l^{5/2} M^{1/2}}, \quad (20)$$

where  $K_c$  is the scale factor.

This expression has following physical sense. Having the length of the IM, we may use (19) to estimate the lowest possible  $W_{Bi}$  level for the given sensor with length  $l$ . Then, using (6) and accepting that for geometrically similar sensors all terms there besides  $M$  may be taken constant and equal to  $K_1$ , we may rewrite expression (6) for the same frequency as

$$W_B = K_1 \cdot M^{-1/2} \quad (21)$$

and find lowest possible  $W_B$  value for this weight. So, we'll get NL estimations for ideal sensor with given  $l$  and  $M$ .

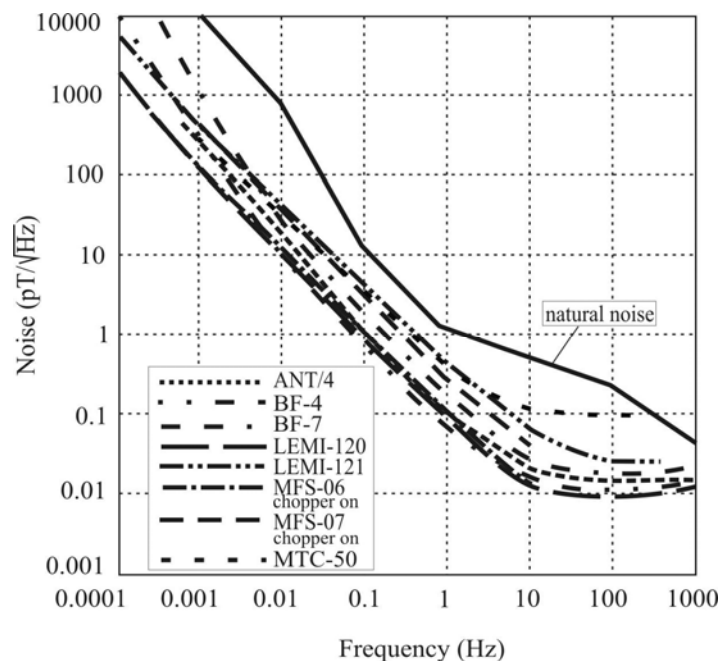
Then for every IM we take real value of  $W_B$  given in their specifications, which is always higher as ideal one, and multiply all values according to the equation (20). Now it is evident that the closer real  $W_B$  is to the ideal  $W_{Bi}$  for given  $l$  and  $M$ , the higher is  $QF$  and the better is the IM.

The efficiency of such an approach was confirmed by the comparison of best known low-frequency IMs (Table 2) which operate in the frequency band from  $\sim 10^{-4}$  till  $\sim 10^3$  Hz: LEMI-120, LEMI-121 (by LC ISR), ANT/4 (by Zonge Engineering), MFS-06, MFS-07 (by Metronix), BF-4, BF-7 (by EMI), MTC-50 (by Phoenix).

**Table 2.** Best commercially available low frequency IMs.

IM	Frequency range, Hz	Sensitivity at flat part of FR	Dimensions, m	Weight, kg	Sensitivity threshold $W_B$ , nT/ $\sqrt{\text{Hz}}$ , at 1 kHz
MTC-50	$2 \cdot 10^{-4} \div 4 \cdot 10^2$	1 V/nT	$l=1.41$ ; $d=0.06$	10.5	$3 \cdot 10^{-4}$
BF-4	$1 \cdot 10^{-4} \div 1 \cdot 10^3$	0.3 V/nT	$l=1.42$ ; $d=0.06$	7.9	$8 \cdot 10^{-5}$
BF-7	$1 \cdot 10^{-4} \div 1 \cdot 10^3$	0.3 V/nT	$l=1.04$ ; $d=0.06$	7	$1.5 \cdot 10^{-4}$
ANT/4	$5 \cdot 10^{-4} \div 1000$	100 mV/nT	$l=1.38$ ; $d=0.048$	6.2	$1 \cdot 10^{-4}$
LEMI-120	$1 \cdot 10^{-4} \div 1 \cdot 10^3$	200 mV/nT	$l=1.38$ ; $d=0.085$	5.8	$1 \cdot 10^{-4}$
MFS-06	$2.5 \cdot 10^{-4} \div 500$	0.2 V/nT	$l=1.25$ ; $d=0.075$	8.5	$1 \cdot 10^{-4}$
MFS-07	$1 \cdot 10^{-3} \div 500$	0.64 V/nT	$l=0.8$ ; $d=0.075$	5.5	$3 \cdot 10^{-4}$
LEMI-121	$1 \cdot 10^{-4} \div 500$	200 mV/nT	$l=0.56$ ; $d=0.085$	4	$5 \cdot 10^{-4}$

It is interesting to compare first their noise plots – see Fig. 5. All of these plots are below the plot representing the natural noise spectrum and are rather close one to another, what shows practical similarity of all best known low-frequency IMs by this parameter, but does not give possibility to say what design is better -  $l$  and  $M$  of these IM are different.

**Fig. 5.** Noise plots for low frequency IMs.

But if to calculate  $QF$  and plot them (Fig. 6), we immediately see the difference: majority of them are rather similar, and only two are out of the cluster (column A). The attempt to compare high frequency

IMs (Table 3) also gives good clustering of their parameters (column B on Fig. 6), whereas their noise plots do not allow the comparison at all (Fig. 7). But if to take specialized IMs, for example for space research, we have very big scattering, what may be also explained: one of the main conditions – geometric similarity – is not observed here and the comparison of their quality needs further research.

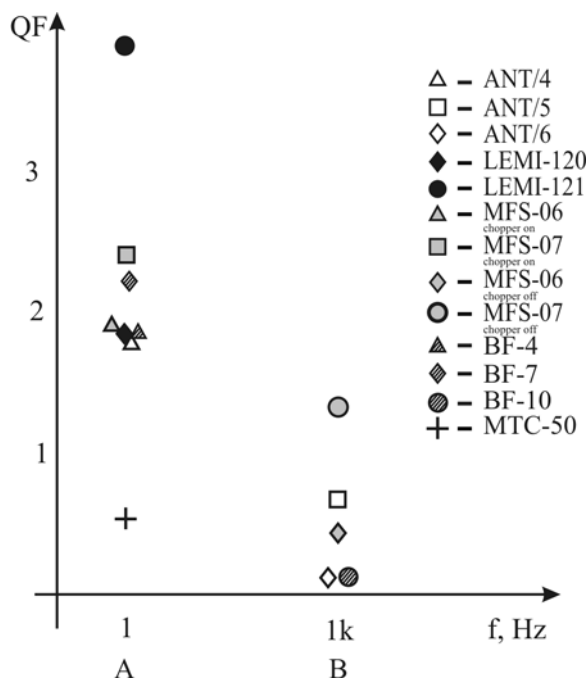
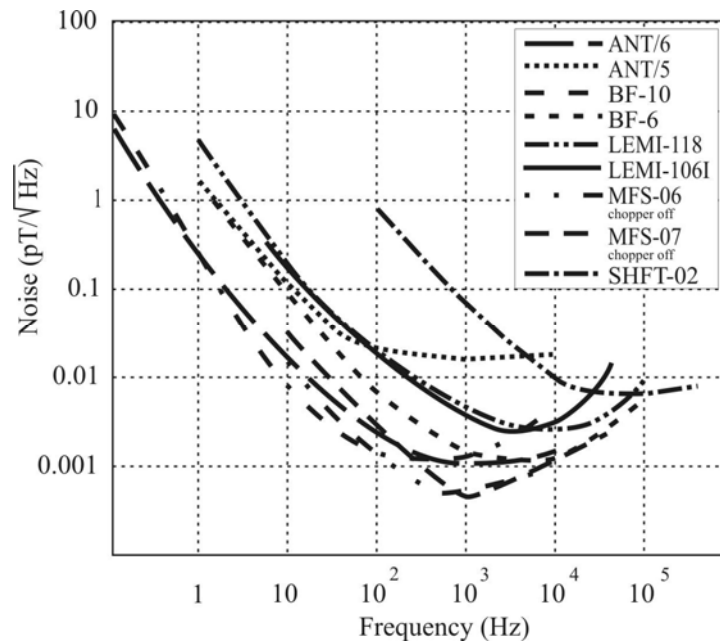


Fig. 6. QF estimation for low frequency and high frequency IMs.

Table 3. Best commercially available high frequency IMs.

IM	Frequency range, Hz	Sensitivity at flat part of FR, mV/nT	Dimensions, m	Weight, kg	Sensitivity threshold $B_{th}$ , nT/ $\sqrt{\text{Hz}}$ , at 1 kHz
BF-6	$1 \cdot 10^5$	300	$l=0.73$ ; $d=0.05$	1.7	$1.5 \cdot 10^{-6}$
BF-10	$0.1 \cdot 10^4$	300	$l=1.42$ ; $d=0.06$	7	$1.5 \cdot 10^{-6}$
ANT/6	$0.1 \cdot 10^4$	200	$l=0.91$ ; $d=0.048$	3.2	$1 \cdot 10^{-6}$
ANT/5	$0.25 \cdot 10^4$	100	$l=0.61$ ; $d=0.036$	1.5	$2 \cdot 10^{-5}$
LEMI-118	$0.1 \cdot 10^5$	20	$l=0.85$ ; $d=0.046$	1.7	$3 \cdot 10^{-5}$
LEMI-106I	$0.5 \cdot 10^5$	20	$l=0.4$ ; $d=0.035$	0.33	$2 \cdot 10^{-5}$
MFS-06	$10 \cdot 10^4$	200	$l=1.25$ ; $d=0.075$	8.5	$5 \cdot 10^{-7}$
MFS-07	$10 \cdot 5 \cdot 10^4$	640	$l=0.8$ ; $d=0.075$	5.5	$5 \cdot 10^{-7}$
SHFT-02	$1 \cdot 10^3 \div 3 \cdot 10^5$	50	$0.17 \times 0.19 \times 0.17$	5.5	$5 \cdot 10^{-5}$



**Fig. 7.** Noise plots for high frequency IMs.

## 6. Conclusions

The aim of this short review of IM design technology was to show that first, to get IM with low noise needs a complicated calculation procedure. Second, it is stated that modern level of different approaches to the IM development is rather similar. This conclusion is confirmed by the comparison of the IM excellence using the proposed quality factor. Though, probably, validity of this comparison is not enough thoroughly substantiated, the users opinion as to different IM types quality, especially for the most widespread – low-frequency IM – is mostly coinciding with given QF estimation. The authors goal was also to stimulate the research in this branch, as far as until now there is not a generalized approach to the IM quality comparison, the need in which is obvious both for commercial reason and for to have though any criterion to pave the way for further attempts of new IM design efficiency estimation.

## Acknowledgements

This work was supported by STCU contract 3165.

## References

- [1]. V. K. Arkadyev, Electromagnetic processes in metals, Part 1, *ONTI*, 1935 (in Russian).
- [2]. R. M. Bozorth and D. M. Chapin, Demagnetization factors of rods, *J. Appl. Phys.*, Vol. 13, 1942, pp. 320-326.
- [3]. M. A. Rozenblat, Demagnetization factors of high permeability rods, *J. Techn. Phys.*, Vol. 24, Issue 4, 1954 (in Russian).
- [4]. K. Varmuth, Über den ballistischen Entmagnetisierungsfactor zylindrischer, Stabe *Arch. f. Elektrotechnik*, Vol. 41, 1954, pp. 242-257.
- [5]. L. Ya. Miziuk, Primary transducers for low-frequency magnetic fields measurement, *Naukova Dumka*, Kyiv, 1964 (in Russian).

- [6]. G. Dehmel, Magnetic field sensors - induction coil (search coil) sensors, Chapter 6 in: Sensors – a comprehensive survey, *VCH Publishers*, 1989, pp. 205-254.
- [7]. F. F. Vakulski, L. Ya. Miziuk, R. V. Prots, Yu. Yu. Sikachevski, Instrumentation for aerogeophysical prospecting with magnetic and electromagnetic informational channels, *Naukova Dumka*, Kyiv, 1985 (in Russian).
- [8]. P. Ripka, Induction Sensors, Chapter 2 in: Magnetic sensors and Magnetometers, *Artech House*, 2001, pp. 47-74.
- [9]. S. Tumanski, Induction coil sensors – a review, *Meas. Sci. Techn.*, 2007, Vol. 18, pp. 31-46.
- [10]. C. Coillot, J. Montoussamy, P. Leroy, G. Chanteur, A. Roux, Improvements on the design of search coil magnetometer for space experiments, *Sensors Letters*, 2007, Vol. 5, pp. 167-170.
- [11]. E. Paperno and A. Grosz, A miniature and ultralow power search coil optimized for a 20 mHz to 2 kHz frequency range, *J. Appl. Phys.*, 2009, Vol. 105, 07E708.
- [12]. V. Korepanov and R. Berkman, New approach to the exact design of low noise search-coil magnetometers, in *Proceedings of XIV IMEKO Word Congress: New measurements - challenges and visions*, Tampere, Finland, 1997, Vol. IVA, Topic 4, pp. 103-108.
- [13]. L. Kadinskaya, To the calculation of the different permeability of cores for magnetomodulation sensors. Technical information bulletin on geophysical instrumentation, Leningrad, 1958 (in Russian).
- [14]. R. Ya. Berkman, Wideband induction magnetometers with minimal weight, in *Proceedings of the V National Symposium of Magnetic Measurements*, Kielce-Borkow, Poland, 22-24 October, 1997, pp. 45 – 52 (in Russian).
- [15]. V. Korepanov and R. Berkman, Comparison of magnetometers efficiency for ELF band, in *Proceedings of the 2<sup>nd</sup> International Conference of Measurement (Measurement'99)*, Smolenice, Slovak Republic, 26-29 April, 1999, pp. 195-198.

---

2010 Copyright ©, International Frequency Sensor Association (IFSA). All rights reserved.  
(<http://www.sensorsportal.com>)

**Fast Universal Frequency-to-Digital Converter**  
**Speed and Performance**

- 16 measuring modes
- 2 channels
- Programmable accuracy up to 0.001 %
- Frequency range: 1 Hz ...7.5 (120) MHz
- Conversion time: 6.25  $\mu$ s ... 6.25 ms
- RS-232, SPI and I<sup>2</sup>C interfaces
- Operating temperature range -40 °C...+85 °C

UFDC-1M-16

[www.sensorsportal.com](http://www.sensorsportal.com)   [info@sensorsportal.com](mailto:info@sensorsportal.com)   SWP, Inc., Toronto, Canada



The Second International Conference  
on Sensor Device Technologies and Applications

## SENSORDEVICES 2011

August 21-27, 2011 - French Riviera, France



### Important deadlines:

Submission deadline	March 23, 2011
Notification	April 30, 2011
Registration	May 15, 2011
Camera ready	May 22, 2011

### Tracks:

- Sensor devices
- Photonics
- Infrared
- Ultrasonic and Piezosensors
- Sensor device technologies
- Sensors signal conditioning and interfacing circuits
- Medical devices and sensors applications
- Sensors domain-oriented devices, technologies, and applications
- Sensor-based localization and tracking technologies

<http://www.iaria.org/conferences2011/SENSORDEVICES11.html>



The Fifth International Conference on Sensor  
Technologies and Applications

## SENSORCOMM 2011

August 21-27, 2011 - French Riviera, France



### Important deadlines:

Submission deadline	March 23, 2011
Notification	April 30, 2011
Registration	May 15, 2011
Camera ready	May 22, 2011

### Tracks:

- APASN: Architectures, protocols and algorithms of sensor networks
- MECSN: Energy, management and control of sensor networks
- RASQOFT: Resource allocation, services, QoS and fault tolerance in sensor networks
- PESMOSN: Performance, simulation and modelling of sensor networks
- SEMOSN: Security and monitoring of sensor networks
- SECSN: Sensor circuits and sensor devices
- RIWISN: Radio issues in wireless sensor networks
- SAPSN: Software, applications and programming of sensor networks
- DAIPSN: Data allocation and information in sensor networks
- DISN: Deployments and implementations of sensor networks
- UNWAT: Under water sensors and systems
- ENOPT: Energy optimization in wireless sensor networks

<http://www.iaria.org/conferences2011/SENSORCOMM11.html>



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

## CENICS 2011

August 21-27, 2011 - French Riviera, France



### Important deadlines:

Submission deadline	March 23, 2011
Notification	April 30, 2011
Registration	May 15, 2011
Camera ready	May 22, 2011

### Tracks:

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

<http://www.iaria.org/conferences2011/CENICS11.html>

## 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. *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

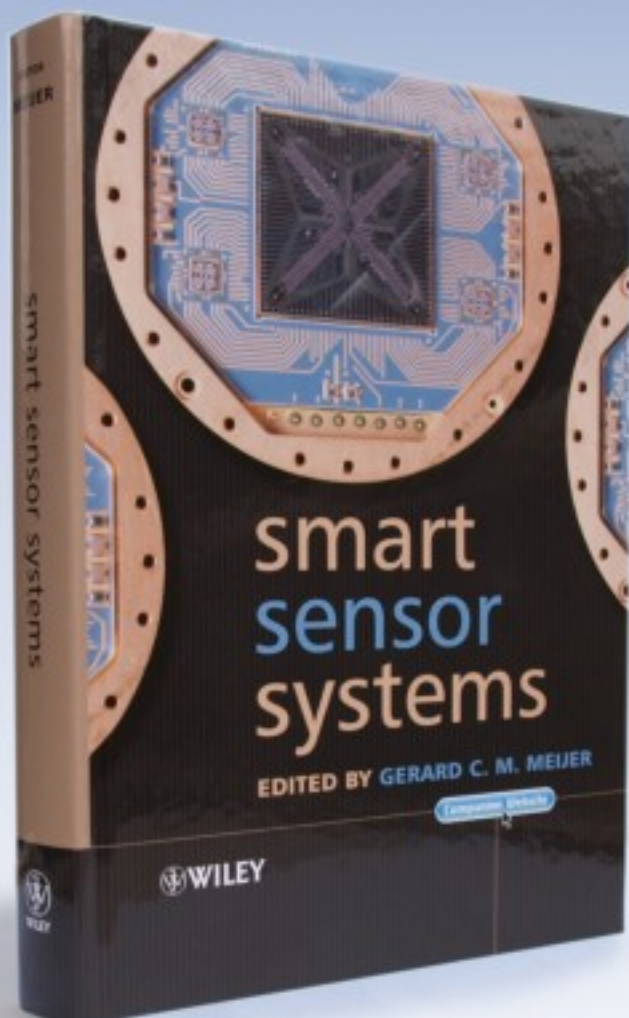
Articles should be written in English. Authors are invited to submit by e-mail [editor@sensorsportal.com](mailto:editor@sensorsportal.com) 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: <http://www.sensorsportal.com/HTML/DIGEST/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](mailto:sales@sensorsportal.com) Please download also our media kit: [http://www.sensorsportal.com/DOWNLOADS/Media\\_Kit\\_2009.pdf](http://www.sensorsportal.com/DOWNLOADS/Media_Kit_2009.pdf)

 **WILEY**  
1807-2007

KNOWLEDGE FOR GENERATIONS



**'Written by an internationally-recognized team of experts, this book reviews recent developments in the field of smart sensors systems, providing complete coverage of all important systems aspects. It takes a multidisciplinary approach to the understanding, design and use of smart sensor systems, their building blocks and methods of signal processing.'**



**Order online:**

[http://www.sensorsportal.com/HTML/BOOKSTORE/Smart\\_Sensor\\_Systems.htm](http://www.sensorsportal.com/HTML/BOOKSTORE/Smart_Sensor_Systems.htm)

**[www.sensorsportal.com](http://www.sensorsportal.com)**