

ISSN 1726-5479

SENSORS & TRANSDUCERS

3<sup>vol. 14-1
Special</sup>
/12



Physical and Chemical Sensors & Wireless Sensor Networks

International Frequency Sensor Association Publishing



Editors-in-Chief: Sergey Y. Yurish, tel.: +34 93 413 7941, 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 for Eastern Europe**

Sachenko, Anatoly, Ternopil State Economic University, Ukraine

Editors for North AmericaDatskos, 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 Africa

Maki K.Habib, American University in Cairo, Egypt

Editor for Asia

Ohyama, Shinji, Tokyo Institute of Technology, Japan

Editor for Asia-Pacific

Mukhopadhyay, Subhas, Massey University, New Zealand

Editorial Advisory Board

- Abdul Rahim, Ruzairi**, Universiti Teknologi, Malaysia
Ahmad, Mohd Noor, Nothern University of Engineering, Malaysia
Annamalai, 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, Vyantas, Kaunas University of Technology, Lithuania
Avachit, Patil Lalchand, North Maharashtra University, India
Ayesh, Aladdin, De Montfort University, UK
Azamimi, Azian binti Abdullah, Universiti Malaysia Perlis, Malaysia
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
Bouchikhi, Benachir, University Moulay Ismail, Morocco
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
Calvo-Gallego, Jaime, Universidad de Salamanca, Spain
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
Dieguez, Angel, University of Barcelona, Spain
Dighavkar, C. G., M.G. Vidyamandir's L. V.H. College, India
Dimitropoulos, Panos, University of Thessaly, Greece
Ding, Jianning, Jiangsu Polytechnic University, China
Djordjevich, Alexandar, City University of Hong Kong, Hong Kong
Donato, Nicola, University of Messina, Italy
Donato, Patricio, Universidad de Mar del Plata, Argentina
Dong, Feng, Tianjin University, China
Drljaca, Predrag, Instersema Sensoric SA, Switzerland
Dubey, Venketesh, Bournemouth University, UK
Enderle, Stefan, Univ.of Ulm and KTB Mechatronics GmbH, Germany
Erdem, Gursan K. Arzum, Ege University, Turkey
Erkmen, Aydan M., Middle East Technical University, Turkey
Estelle, Patrice, Insa Rennes, France
Estrada, Horacio, University of North Carolina, USA
Faiz, Adil, INSA Lyon, France
Fericean, Sorin, Balluff GmbH, Germany
Fernandes, Joana M., University of Porto, Portugal
Francioso, Luca, CNR-IMM Institute for Microelectronics and Microsystems, Italy
Francis, Laurent, University Catholique de Louvain, Belgium
Fu, Weiling, South-Western Hospital, Chongqing, China
Gaura, Elena, Coventry University, UK
Geng, Yanfeng, China University of Petroleum, China
Gole, James, Georgia Institute of Technology, USA
Gong, Hao, National University of Singapore, Singapore
Gonzalez de la Rosa, Juan Jose, University of Cadiz, Spain
Grael, 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
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
Kaniasus, 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
Khelfaoui, Rachid, Université de Bechar, Algeria
Khan, Asif, Aligarh Muslim University, Aligarh, India
Kim, Min Young, Kyungpook National University, Korea South
Ko, Sang Choon, Electronics. and Telecom. Research Inst., Korea South
Kotulska, Malgorzata, Wroclaw University of Technology, Poland
Kockar, Hakan, Balikesir University, Turkey

Kong, Ing, RMIT University, Australia
Kratz, Henrik, Uppsala University, Sweden
Krishnamoorthy, Ganesh, University of Texas at Austin, USA
Kumar, Arun, University of Delaware, Newark, 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, Fengyuan (Thomas), Purdue University, USA
Li, Genxi, Nanjing University, China
Li, Hui, Shanghai Jiaotong University, China
Li, Xian-Fang, Central South University, China
Li, Yuefa, Wayne State University, USA
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
Malyshev, V.V., National Research Centre 'Kurchatov Institute', Russia
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, Benemerita 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
Mrad, Nezih, Defence R&D, Canada
Mulla, Imtiaz Sirajuddin, National Chemical Laboratory, Pune, India
Nabok, Aleksey, Sheffield Hallam University, UK
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 Seteбал, 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
Pugno, Nicola M., Politecnico di Torino, Italy
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
Rastogi Shiva, K., University of Idaho, USA
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
Sapozhnikova, Ksenia, D.I.Mendeleyev Institute for Metrology, Russia
Sandacci, Serghei, Sensor Technology Ltd., UK
Saxena, Vibha, Bbhba Atomic Research Centre, Mumbai, India
Schneider, John K., Ultra-Scan Corporation, USA
Sengupta, Deepak, Advance Bio-Photonics, India
Seif, Selemeni, Alabama A & M University, USA
Seifter, Achim, Los Alamos National Laboratory, USA
Shah, Kriyang, La Trobe University, Australia
Sankarraj, Anand, Detector Electronics Corp., USA
Silva Girao, Pedro, Technical University of Lisbon, Portugal
Singh, V. R., National Physical Laboratory, India
Slomovitz, Daniel, UTE, Uruguay
Smith, Martin, Open University, UK
Soleymanpour, Ahmad, Damghan Basic Science University, Iran
Somani, Prakash R., Centre for Materials for Electronics Technol., India
Sridharan, M., Sastra University, India
Srinivas, Talabattula, Indian Institute of Science, Bangalore, India
Srivastava, Arvind K., NanoSonix Inc., USA
Stefan-van Staden, Raluca-Ioana, University of Pretoria, South Africa
Stefanescu, Dan Mihai, Romanian Measurement Society, Romania
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, Zhiqing, 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
Thirunavukkarasu, I., Manipal University Karnataka, India
Thumavanam 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, Sen, Drexel University, USA
Xu, Tao, University of California, Irvine, USA
Yang, Dongfang, National Research Council, Canada
Yang, Shuang-Hua, Loughborough University, UK
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, Qintao, University of California at Berkeley, USA
Zhang, Weiping, Shanghai Jiao Tong University, China
Zhang, Wenming, Shanghai Jiao Tong University, China
Zhang, Xueji, World Precision Instruments, Inc., USA
Zhong, Haoxiang, Henan Normal University, China
Zhu, Qing, Fujifilm Dimatix, Inc., USA
Zorzano, Luis, Universidad de La Rioja, Spain
Zourob, Mohammed, University of Cambridge, UK

Contents

Volume 14-1
Special Issue
March 2012

www.sensorsportal.com

ISSN 1726-5479

Research Articles

| | |
|--|-----|
| Physical and Chemical Sensors & Wireless Sensor Networks (Foreword) <i>Sergey Y. Yurish, Petre Dini</i> | 1 |
| From Smart to Intelligent Sensors: A Case Study <i>Vincenzo Di Lecce, Marco Calabrese</i> | 1 |
| Smart Optoelectronic Sensors and Intelligent Sensor Systems <i>Sergey Y. Yurish</i> | 18 |
| Accelerometer and Magnetometer Based Gyroscope Emulation on Smart Sensor for a Virtual Reality Application <i>Baptiste Delporte, Laurent Perroton, Thierry Grandpierre and Jacques Trichet</i> | 32 |
| Top-Level Simulation of a Smart-Bolometer Using VHDL Modeling <i>Matthieu Denoual and Patrick Attia</i> | 48 |
| A Novel Liquid Level Sensor Design Using Laser Optics Technology <i>Mehmet Emre Erdem and Doğan Güneş</i> | 65 |
| Recognition of Simple Gestures Using a PIR Sensor Array <i>Piotr Wojtczuk, Alistair Armitage, T. David Binnie, Tim Chamberlain</i> | 83 |
| Sinusoidal Calibration of Force Transducers Using Electrodynamic Shaker Systems <i>Christian Schlegel, Gabriela Kiekenap, Bernd Glöckner, Rolf Kumme</i> | 95 |
| Experimental Validation of a Sensor Monitoring Ice Formation over a Road Surface <i>Amedeo Troiano, Eros Pasero, Luca Mesin</i> | 112 |
| Acoustic Emission Sensing of Structures under Stretch <i>Irinela Chilibon, Marian Mogildea, George Mogildea</i> | 122 |
| Differential Search Coils Based Magnetometers: Conditioning, Magnetic Sensitivity, Spatial Resolution <i>Timofeeva Maria, Allegre Gilles, Robbes Didier, Flament Stéphane</i> | 134 |
| Silicon Photomultipliers: Dark Current and its Statistical Spread <i>Roberto Pagano, Sebania Libertino, Giusy Valvo, Alfio Russo, Delfo Nunzio Sanfilippo, Giovanni Condorelli, Clarice Di Martino, Beatrice Carbone, Giorgio Fallica and Salvatore Lombardo</i> | 151 |
| An Integrated Multimodal Sensor for the On-site Monitoring of the Water Content and Nutrient Concentration of Soil by Measuring the Phase and Electrical Conductivity <i>Masato Futagawa, Md. Iqramul Hussain, Keita Kamado, Fumihito Dasai, Makoto Ishida, Kazuaki Sawada</i> | 160 |
| Design and Evaluation of Impedance Based Sensors for Micro-condensation Measurement under Field and Climate Chamber Conditions <i>Geert Brokmann, Michael Hintz, Barbara March and Arndt Steinke</i> | 174 |

| | |
|---|-----|
| A Parallel Sensing Technique for Automatic Bilayer Lipid Membrane Arrays Monitoring <i>Michele Rossi, Federico Thei and Marco Tartagni</i> | 185 |
| Development of Acoustic Devices Functionalized with Cobalt Corroles or Metalloporphyrines for the Detection of Carbon Monoxide at Low Concentration <i>Meddy Vanotti, Virginie Blondeau-Patissier, David Rabus, Jean-Yves Rauch, Jean-Michel Barbe, Sylvain Ballandras</i> | 197 |
| Group IV Materials for High Performance Methane Sensing in Novel Slot Optical Waveguides at 2.883 μm and 3.39 μm <i>Vittorio M. N. Passaro, Benedetto Troia and Francesco De Leonardis</i> | 212 |
| The Impact of High Dielectric Permittivity on SOI Double-Gate Mosfet Using Nextnano Simulator <i>Samia Slimani, Bouaza Djellouli</i> | 231 |
| A Novel Sensor for VOCs Using Nanostructured ZnO and MEMS Technologies <i>H. J. Pandya, Sudhir Chandra and A. L. Vyas</i> | 244 |
| La_{0.7}Sr_{0.3}MnO₃ Thin Films for Magnetic and Temperature Sensors at Room Temperature <i>Sheng Wu, Dalal Fadil, Shuang Liu, Ammar Aryan, Benoit Renault, Jean-Marc Routoure, Bruno Guillet, Stéphane Flament, Pierre Langlois and Laurence Méchin</i> | 253 |
| Cell-Culture Real Time Monitoring Based on Bio-Impedance Measurements <i>Paula Daza, Daniel Cañete, Alberto Olmo, Juan A. García and Alberto Yúfera</i> | 266 |

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).

BioMEMS 2010

Yole's BioMEMS report 2010-2015

IFSA offers
a SPECIAL PRICE

Microsystems Devices Driving Healthcare Applications

The BioMEMS 2010 report is a robust analysis of the Micro Devices with the most advances to develop solutions for vital bio-medical applications. The devices considered are:

| | |
|--------------------------------|---|
| Pressure sensors | Microfluidic chips |
| Silicon microphones | Microdispensers for drug delivery |
| Accelerometers | Flow meters |
| Gyroscopes | Infrared temperature sensors |
| Optical MeMs and image sensors | Emerging MeMs (rfID, strain sensors, energy harvesting) |

Also addressed are the regulation aspects for medical device development.

<http://www.sensorsportal.com/HTML/BioMEMS.htm>



The 3rd International Conference on Sensor Device Technologies and Applications



SENSORDEVICES 2012

19 - 24 August 2012 - Rome, Italy

Deadline for papers: 5 April 2012



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

<http://www.iaia.org/conferences2012/SENSORDEVICES12.html>

The 6th International Conference on Sensor Technologies and Applications



SENSORCOMM 2012

19 - 24 August 2012 - Rome, Italy

Deadline for papers: 5 April 2012



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

<http://www.iaia.org/conferences2012/SENSORCOMM12.html>

The 5th International Conference on Advances in Circuits, Electronics and Micro-electronics



CENICS 2012

19 - 24 August 2012 - Rome, Italy

Deadline for papers: 5 April 2012



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

<http://www.iaia.org/conferences2012/CENICS12.html>

Accelerometer and Magnetometer Based Gyroscope Emulation on Smart Sensor for a Virtual Reality Application

**Baptiste Delporte, Laurent Perroton, Thierry Grandpierre
and ¹Jacques Trichet**

Université Paris Est, ESIEE Engineering, Marne-la-vallée, France

¹Freescale Semiconductor, Inc. Toulouse, France

Received: 16 November 2011 /Accepted: 20 December 2011 /Published: 12 March 2012

Abstract: In this paper, we propose two methods based on quaternions to compute the angles of inclination and the angular velocity with 6 degrees of freedom using the measurements of a 3-axis accelerometer and a 3-axis magnetometer. Each method has singularities which occur during the computation of the orientation of the device in the 3-dimensional space. We propose solutions to avoid these singularities. Experimental results are given to compare our model with a real gyroscope. *Copyright © 2012 IFSA.*

Keywords: Smart sensor, Sensor fusion, Accelerometer, Magnetometer, Angular velocity, Gyroscope.

1. Introduction

The computation of the angles of inclination of a device and its angular velocity has many applications for aeronautics, transportation systems, human motion tracking, games and virtual reality. Classical methods use accelerometers, magnetometers and gyroscopes. For some particular angles, there are singularities for which it is impossible to compute neither the orientation of the device in the 3-dimensional space nor its angular velocity [8, page 407].

Our goal is to design a smart sensor magnetometer based virtual gyroscope, i.e. a method to compute the angular velocity based on the measurements of a 3-axis accelerometer and a 3-axis magnetometer, without any gyroscope, and with 6 degrees of freedom: 3 degrees of freedom are provided by the accelerometer and the others are provided by the magnetometer. It is easier to implement, less expensive and has lower power consumption than the classical gyroscope solutions. Our target is small motion tracking with embedded devices like cellular phones, with application fields like virtual or

augmented reality. Moreover, it is possible to create a virtual gyroscope with a magnetometer and an accelerometer, whereas it is not possible to create a virtual magnetometer or a virtual accelerometer using only a gyroscope. Methods with accelerometers only have been already proposed in [2, 3, 6, 7].

A well-known method to compute a strap down gyroscope output simply consists in differentiating the angles of inclination of the device, but we want to compute the total angular velocity, which is the addition of the angular velocities about the three axes of the fixed frame.

Two methods with two different approaches have been developed. They are proposed in this paper. The method that uses the angles of inclination of the device has been implemented. The method that uses the rotation matrix will be implemented and the two methods will be compared in order to find the method which offers the best precision on the target architecture. This work is a collaboration project between Freescale and ESIEE Engineering School which started in June 2010.

In Section 2, we introduce the platform and the sensors. In Section 3, a first method to compute the angular velocity using the absolute angles of inclination is presented. In Section 4, a second method to compute the angular velocity using the rotation matrix is presented. In Section 5, experimental results are given and a virtual reality application is presented.

2. Hardware and Smart Sensors

We use the new Freescale MMA9550L smart sensor (Figure 1). This motion sensing platform can manage multiple sensor inputs. It includes a 3-axis accelerometer and a ColdFire V1 32-bit microcontroller unit (MCU) with an integrated Multiply and ACcumulate module (MAC module) for DSP-like operations. An additional Honeywell HMC5843 3-axis magnetometer is mounted on the MMA9550L board so that the two sensors are strictly parallel and their frames are aligned.

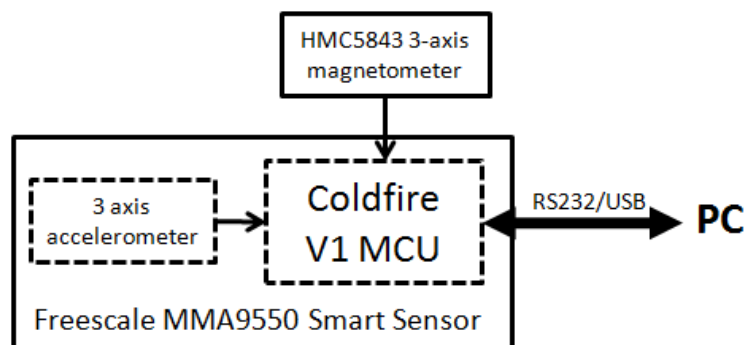


Fig. 1. Hardware board.

This paper focuses on the mathematical model which provides the angular velocity and the angles of inclination of the device in the 3-dimensional space. The algorithms have been implemented in the form of MATLAB scripts for testing purposes and the curves show the results of these implementations. Once validated, the algorithms have been implemented in C on a Windows 32bits platform for the virtual reality application presented at the last section of the article. In the future, the algorithms will be directly implemented on the MMA9550L, since it includes its own microprocessor.

3. Virtual Gyroscope Based on the Angles of Inclination of the Device

In this section, the angles of inclination and the angular velocity are computed from the accelerometer and the magnetometer measurements using Tait-Bryan angles and quaternions.

3.1. Parameterization of Rotations with Tait-Bryan Angles

In order to describe the orientation of the device in the 3-dimensional space, 2 right-handed Cartesian coordinate systems are used: a fixed reference frame with $X_r = \text{North}$, $Y_r = \text{East}$ and $Z_r = \text{Down}$ (NED convention), and denoted by the subscript r , and a moving frame attached to a mobile device, denoted by the subscript d . The reference frame and the device frame are aligned when the device is flat and aligned with the X_d axis pointed to magnetic North. Rotation angles are positive when clockwise viewed along the relevant axis vector in the positive direction.

The orientation of the device in the reference frame can be described by Tait-Bryan angles: ϕ , θ and ψ . ψ is the angle of rotation about the Z_r axis (yaw). θ is the angle of rotation about the Y_r axis (pitch). ϕ is the angle of rotation about the X_r axis (roll). Any rotation of the device can be expressed as a composition of these three rotations in the reference frame, as shown in Fig. 2.

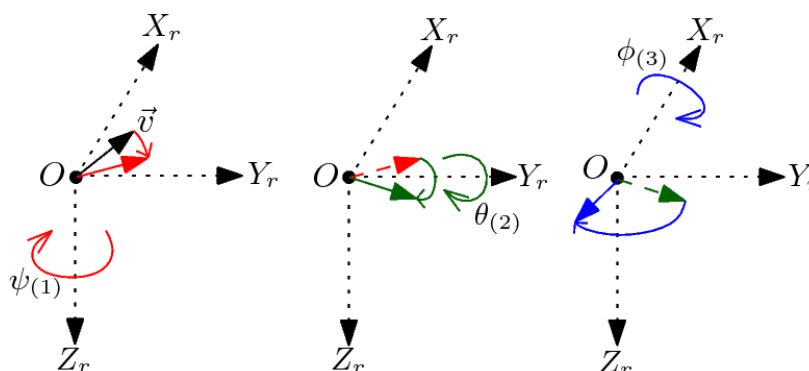


Fig. 2. Tait-Bryan angles.

A rotation about the Z_r axis, the Y_r axis or the X_r axis can be respectively described by a rotation matrix $R_z(\psi)$, $R_y(\theta)$ or $R_x(\phi)$:

$$R_z(\psi) = \begin{pmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad R_y(\theta) = \begin{pmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{pmatrix}$$

$$R_x(\phi) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & \sin(\phi) \\ 0 & -\sin(\phi) & \cos(\phi) \end{pmatrix}$$

The composition of the 3 rotations about the Z_r axis, then the Y_r axis and finally the X_r axis, is described by the rotation matrix $R(\phi, \theta, \psi) = R_x(\phi) \cdot R_y(\theta) \cdot R_z(\psi)$.

It is possible to compute ϕ , θ , ψ and the angular velocity $\vec{\omega}$ from the Earth's magnetic field \vec{B}_d , expressed in the device frame, and the Earth's gravitational field \vec{g}_d , expressed in the device frame.

The magnetic field is measured by the magnetometer. On the other hand, the accelerometer measures the total acceleration including the gravitational field, the acceleration provided by the user and the acceleration due to the Coriolis force. Consequently, an extraction of the gravitational field \vec{g}_d needs to be performed with a filter.

The expression of the Earth's magnetic field in the reference frame is given by $\vec{B}_r = (B \cdot \cos(\delta) \ 0 \ B \cdot \sin(\delta))^T$ where B denotes the strength of the magnetic field (in Teslas), δ denotes the angle of inclination of the magnetic field, which depends on the location on the Earth, and $(\cdot)^T$ denotes the transpose of (\cdot) .

The expression of the Earth's gravitational field in the reference frame is given by $\vec{g}_r = (0 \ 0 \ g)^T$ where g denotes the strength of the gravitational field, i.e. the acceleration (in Newtons). The computation process is shown in Fig. 3.

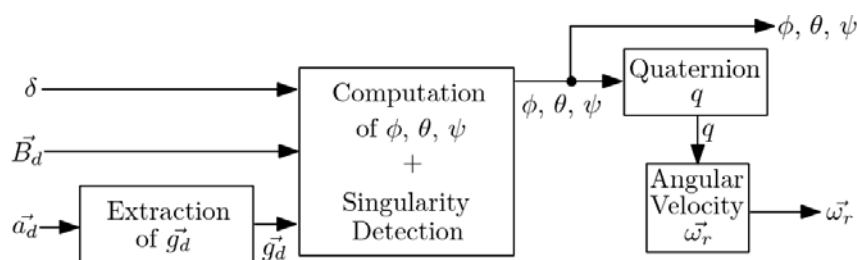


Fig. 3. Computation process 1.

3.2. Extraction of \vec{g}_d

Since \vec{g}_d is a constant offset in the measurement of \vec{a}_d , it can be extracted with a low-pass filter. The resulting vector \vec{g}_e contains sensor medium frequencies and spurious noise. In order to keep only \vec{g}_d , a sliding median filter and a sliding average filter are used, as shown in Fig. 4. The same delay is applied to \vec{B}_d to make sure they are in phase.

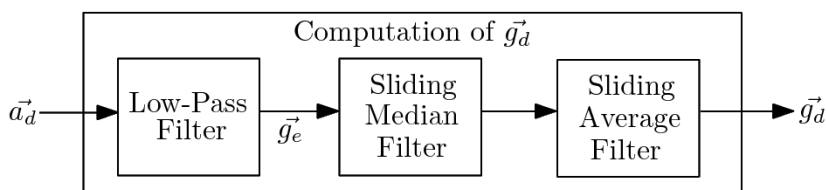


Fig. 4. Computation of \vec{g}_d .

3.2.1. Low-Pass Filter

The frequency of \vec{g}_d equals 0. Consequently, the gravitational field can be extracted with a first-order Butterworth low-pass filter. The Z-transform transfer function of the filter is given by:

$$\frac{g_e(z)}{a_d(z)} = \frac{b_0 + b_1 \cdot z^{-1}}{1 + a_1 \cdot z^{-1}}$$

The default coefficients have been computed with MATLAB by synthesizing a low-pass filter with an experimentally determined cut-off frequency $F_c = 0.02.F_s$, where F_s denotes the sampling frequency. They are given by $[b_0, b_1, a_1] = [0.0305, 0.0305, -0.9391]$. If a variation of the norm $\|\vec{g}_d\|$ exceeds a threshold, the cut-off frequency of the Butterworth filter increases of $0.05.F_s$ and the coefficients $[b_0, b_1, a_1]$ are computed again. If the cut-off frequency reaches $F_c = 0.4.F_s$, the filter waits for the norm $\|\vec{g}_d\|$ to stabilize. Then, F_c decreases of $0.05.F_s$ until it reaches $0.02.F_s$. Then, F_c is kept, until the norm $\|\vec{g}_d\|$ exceeds again the threshold. A threshold of $\Delta_{g_d} = \frac{1}{100} \|\vec{g}_d\|$ has been experimentally determined.

3.2.2. Sliding Median Filter

A sliding median filter is used in order to eliminate the highest frequencies sensor spurious noise, which creates variations of the norm of \vec{g}_d . Since this norm should be constant, we need to eliminate the samples that have an erroneous norm. As we will see in section 3.3, \vec{g}_d directly impacts the accuracy of the entire computation process, hence the need to get \vec{g}_d with the least error. The sliding median filter uses a sliding window of n norms. At the beginning, the window contains the first n norms of the first n samples. Then, the norms of the window are sorted. Finally, the median value of the window is extracted, and the sample whose norm is the median value is output from the filter, as shown in Fig. 5.

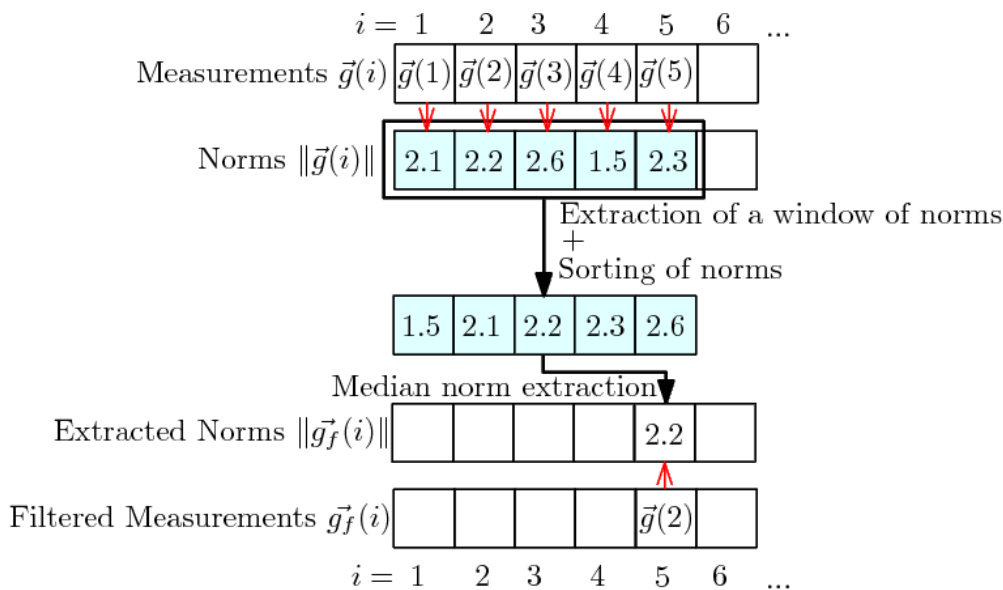


Fig. 5. Sliding Median Filter.

Let $\vec{g} = (g_x \ g_y \ g_z)^T$ be the input vector, $\vec{g}_f = (g_{fx} \ g_{fy} \ g_{fz})^T$ the filtered vector and i the index of the sample. The expression of the filter is given by:

$$\vec{g}_f(i) = \vec{g}(i) \text{ such that } \|\vec{g}(i)\| = \text{median} \left(\|\vec{g}(t-n+1 \dots t)\| \right)$$

Then, the window slides to the right and the norms of $\vec{g}(i - n + 2 \dots i + 1)$ are extracted. A sliding median filter creates a delay of $n - 1$ samples.

The gravitational field filtered with the sliding median filter still has variations, a sliding average filter is used to smooth it.

3.2.3. Sliding Average Filter

The sliding average filter uses a sliding window of n samples. At the beginning, the window contains the first n samples. Then, the average value of the window is extracted and output from the filter.

Let $\vec{g} = (g_x \ g_y \ g_z)^T$ be the input vector, $\vec{g}_f = (g_{fx} \ g_{fy} \ g_{fz})^T$ the filtered vector and i the index of the sample. The expression of the filter is given by:

$$\vec{g}_f(i) = \frac{1}{n} \cdot \sum_{k=i-n+1}^i \vec{g}(k)$$

Then, the window slides to the right and filters the values $\vec{g}(i - n + 2 \dots i + 1)$. A sliding average filter creates a delay of $n - 1$ samples.

3.3. Computation of the Angles of Inclination

The Earth's magnetic field \vec{B}_d , expressed in the device frame, results from the rotation of the magnetic field \vec{B}_r , expressed in the reference frame.

$$\vec{B}_d = R_x(\phi) \cdot R_y(\theta) \cdot R_z(\psi) \cdot \vec{B}_r \quad (1)$$

The Earth's gravitational field \vec{g}_d , expressed in the device frame, results from the rotation of the gravitational field \vec{g}_r , expressed in the reference frame. Since \vec{g}_r remains unchanged after a rotation about the Z_r axis, $R_z(\psi) \cdot \vec{g}_r = \vec{g}_r$. It follows:

$$\vec{g}_d = R_x(\phi) \cdot R_y(\theta) \cdot \vec{g}_r \quad (2)$$

It is possible to compute the roll angle ϕ from the gravitational field by developing Eq. 2:

$$\phi_g = \arctan2 \left(\frac{g_{dy}}{g_{dx}} \right) \quad (3)$$

$\arctan2$ denotes the arctangent on the domain $[-\pi, \pi]$.

Once ϕ is known, it is possible to compute θ :

$$\theta = \arctan \left(\frac{-g_{dx}}{g_{dy} \cdot \sin(\phi) + g_{dz} \cdot \cos(\phi)} \right) \quad (4)$$

arctan denotes the arctangent on the domain $\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$.

If \vec{O}_d is aligned with the X_d axis, the denominator in Eq. 4 becomes 0. Please see Table 1 for the detection of this singularity.

Table 1. Table of Singularities.

| g_{dNx} | g_{dNy} | B_{dNx} | B_{dNy} | ϕ | θ | ψ |
|-----------|-----------|-----------------|-----------------|------------------|------------------|------------------|
| 1 | 0 | $\sin(\delta)$ | $\cos(\delta)$ | $-\frac{\pi}{2}$ | $-\frac{\pi}{2}$ | 0 |
| | | | | 0 | $-\frac{\pi}{2}$ | $-\frac{\pi}{2}$ |
| | | | | $\frac{\pi}{2}$ | $-\frac{\pi}{2}$ | $\frac{\pi}{2}$ |
| | | | | π | $-\frac{\pi}{2}$ | $\frac{\pi}{2}$ |
| 1 | 0 | $\sin(\delta)$ | $-\cos(\delta)$ | $-\frac{\pi}{2}$ | $-\frac{\pi}{2}$ | 0 |
| | | | | 0 | $-\frac{\pi}{2}$ | $\frac{\pi}{2}$ |
| | | | | $\frac{\pi}{2}$ | $-\frac{\pi}{2}$ | $\frac{\pi}{2}$ |
| | | | | π | $-\frac{\pi}{2}$ | $-\frac{\pi}{2}$ |
| 0 | -1 | $\cos(\delta)$ | $-\sin(\delta)$ | $-\frac{\pi}{2}$ | 0 | 0 |
| | | | | $\frac{\pi}{2}$ | π | π |
| 0 | -1 | $-\cos(\delta)$ | $-\sin(\delta)$ | $-\frac{\pi}{2}$ | 0 | π |
| | | | | $\frac{\pi}{2}$ | π | 0 |
| -1 | 0 | $-\sin(\delta)$ | $-\cos(\delta)$ | $-\frac{\pi}{2}$ | $\frac{\pi}{2}$ | 0 |
| | | | | 0 | $\frac{\pi}{2}$ | $\frac{\pi}{2}$ |
| | | | | $\frac{\pi}{2}$ | $\frac{\pi}{2}$ | $\frac{\pi}{2}$ |
| | | | | π | $\frac{\pi}{2}$ | $-\frac{\pi}{2}$ |
| -1 | 0 | $-\sin(\delta)$ | $-\cos(\delta)$ | $-\frac{\pi}{2}$ | $\frac{\pi}{2}$ | $\frac{\pi}{2}$ |
| | | | | 0 | $\frac{\pi}{2}$ | $-\frac{\pi}{2}$ |
| | | | | $\frac{\pi}{2}$ | $\frac{\pi}{2}$ | 0 |
| | | | | π | $\frac{\pi}{2}$ | $\frac{\pi}{2}$ |
| 0 | -1 | $-\cos(\delta)$ | $\sin(\delta)$ | $-\frac{\pi}{2}$ | 0 | 0 |
| | | | | $\frac{\pi}{2}$ | 0 | π |
| 0 | -1 | $\cos(\delta)$ | $\sin(\delta)$ | $-\frac{\pi}{2}$ | 0 | 0 |
| | | | | $\frac{\pi}{2}$ | 0 | π |

Once ϕ and θ are known, it is possible to compute ψ by developing Eq. 1:

$$\psi = \arctan2 \left(\frac{B_{dx} \cdot \sin(\phi) - B_{dy} \cdot \cos(\phi)}{B_{dx} \cdot \cos(\theta) + B_{dy} \cdot \sin(\phi) \cdot \sin(\theta) + B_{dz} \cdot \sin(\theta) \cdot \cos(\phi)} \right)$$

3.4. Singularity Detection

A table of the singularities is given in Table 1. The normalized gravitational and magnetic field in the device frame are denoted respectively by

$$\vec{g}_{dN} = (g_{dNx} \quad g_{dNy} \quad g_{dNz})^T = \frac{\vec{g}_d}{\|\vec{g}_d\|}$$

and

$$\vec{B}_{dN} = (B_{dNx} \quad B_{dNy} \quad B_{dNz})^T = \frac{\vec{B}_d}{\|\vec{B}_d\|}.$$

If a singularity is detected, several compositions of rotations give the same result. Consequently, there are two methods. The first method consists in keeping the previous values of ϕ , θ and ψ . The second method consists in finding the appropriate case that allows the accurate determination of ϕ , θ and ψ .

3.5. Parameterization of Rotations with Quaternions

The quaternions are hypercomplex numbers, i.e. 4-dimensional mathematical objects, used to describe rotations in the 3-dimensional space [5].

3.5.1. Definition and Properties of a Quaternion

A quaternion q has 4 coordinates in a 4-dimensional vector space and is denoted by $q = (q_1 \quad q_2 \quad q_3 \quad q_4)^T$ with $(q_1 \quad q_2 \quad q_3 \quad q_4) \in \mathbb{R}^4$. It consists of a vector part $q_v = (q_1 \quad q_2 \quad q_3)^T$ and a scalar part $q_s = q_4$. It can be expressed in the following form:

$$q = q_1 \cdot 1 + q_2 \cdot j + q_3 \cdot k + q_4 \quad (5)$$

In Eq. 5, i , j and k are imaginary numbers: $i^2 = j^2 = k^2 = -1$, and $i \cdot j = -j \cdot i = k$, $j \cdot k = -k \cdot j = i$, $k \cdot i = -i \cdot k = j$. Therefore, it is possible to compute the product of two quaternions $q = (q_1 \quad q_2 \quad q_3 \quad q_4)^T$ and $q' = (q'_1 \quad q'_2 \quad q'_3 \quad q'_4)^T$, denoted by $q \cdot q'$, using the properties of the hypercomplex numbers. It can be noticed that the product between 2 quaternions is not commutative: $q \cdot q' \neq q' \cdot q$.

The inverse of a quaternion $q = (q_1 \quad q_2 \quad q_3 \quad q_4)^T$ is denoted by $q^{-1} = (-q_1 \quad -q_2 \quad -q_3 \quad q_4)^T$.

3.5.2. Euler-Rodrigues Parameters

A quaternion $q = (q_1 \quad q_2 \quad q_3 \quad q_4)^T$ can be used to describe a rotation by an angle α about a unit

vector $\vec{a} = (a \ b \ c)^T$ that is the axis. \vec{a} is a unit vector, so $\|\vec{a}\| = 1$. The Euler-Rodrigues parameters corresponding to the rotation are given by:

$$q_1 = a \cdot \sin\left(\frac{\alpha}{2}\right) \quad q_2 = a \cdot \sin\left(\frac{\alpha}{2}\right) \cdot i \quad q_3 = a \cdot \sin\left(\frac{\alpha}{2}\right) \cdot j \quad q_4 = \cos\left(\frac{\alpha}{2}\right)$$

3.5.3. Rotation

Let $\vec{v} = (x \ y \ z)^T$ be a vector. The quaternion q transforms \vec{v} into another vector $\vec{v}_f = (x_f \ y_f \ z_f)^T$ by rotating it by angle α about an \vec{a} axis. A fourth null coordinate is added to \vec{v} , so it becomes $\vec{v}_q = (x \ y \ z \ 0)^T$. The rotated vector \vec{v}_f corresponds to the vector part of \vec{v}_{fq} given by:

$$\vec{v}_{fq} = q \cdot \vec{v}_q \cdot q^{-1} \quad (6)$$

The scalar part of \vec{v}_{fq} is 0, since \vec{v}_{fq} is a pure vector in the 3-dimensional space.

3.5.4. Composition of Two Rotations

Let q_α be a quaternion describing a rotation by an angle α about an axis \vec{a} and q_β a quaternion describing a rotation by an angle β about an axis \vec{b} . The composition of the rotations about the \vec{b} axis, then the \vec{a} axis, is given by the quaternion $q_{\alpha,\beta} = q_\alpha \cdot q_\beta$. Let $\vec{v} = (x \ y \ z)^T$ be a vector. The quaternion $q_{\alpha,\beta}$ transforms \vec{v} into another vector $\vec{v}_f = (x_f \ y_f \ z_f)^T$ by rotating it by angle β about an axis \vec{b} , then by angle α about an axis \vec{a} . With $\vec{v}_q = (x \ y \ z \ 0)^T$, the expression of Eq. 6 becomes $\vec{v}_{fq} = (q_\alpha \cdot q_\beta) \cdot \vec{v}_q \cdot (q_\beta^{-1} \cdot q_\alpha^{-1})$. The rotated vector \vec{v}_f corresponds to the vector part of \vec{v}_{fq} . The scalar part of \vec{v}_{fq} is 0, since \vec{v}_{fq} is a pure vector in the 3-dimensional space.

3.5.5. Computation of the Angular Velocity

The instantaneous angular velocity $\vec{\omega}_r(t)$ of the device at the instant t , expressed in the reference frame, corresponds to the vector part of $\vec{\omega}_{rq}(t)$ given by [4]:

$$\vec{\omega}_{rq}(t) = 2 \cdot q^{-1}(t) \cdot \frac{dq(t)}{dt}$$

The scalar part of $\vec{\omega}_{rq}(t)$ is 0, since $\vec{\omega}_{rq}(t)$ is a pure vector in the 3-dimensional space, which finally gives:

$$\vec{\omega}_r(t) = \begin{pmatrix} \cos(\theta) \cdot \cos(\psi) \cdot \dot{\phi} + \sin(\psi) \cdot \dot{\theta} \\ -\cos(\theta) \cdot \sin(\psi) \cdot \dot{\phi} + \cos(\psi) \cdot \dot{\theta} \\ \sin(\theta) \cdot \dot{\phi} + \dot{\psi} \end{pmatrix}$$

3.6. Computation of the Quaternion q From the Angles of Inclination

A rotation by angle ψ about the Z_r axis, by angle θ about the Y_r axis or by angle ϕ about the X_r axis can be respectively described by the quaternion

$$q_\psi = \left(0 \ 0 \ \sin\left(\frac{\psi}{2}\right) \ \cos\left(\frac{\psi}{2}\right) \right)^T,$$

$$q_\theta = \left(0 \ \sin\left(\frac{\theta}{2}\right) \ 0 \ \cos\left(\frac{\theta}{2}\right) \right)^T,$$

or

$$q_\phi = \left(\sin\left(\frac{\phi}{2}\right) \ 0 \ 0 \ \cos\left(\frac{\phi}{2}\right) \right)^T.$$

The quaternion describing the composition of the rotations about the Z_r axis, then the Y_r axis, and finally the X_r axis, is given by $q = q_\phi \cdot q_\theta \cdot q_\psi$.

The method described above has 8 singularities. Consequently, the computation of the angles ϕ , θ and ψ cannot be accurate if the detection of singularities is not efficient enough.

4. Virtual Gyroscope Based on the Rotation Matrix

In this section, the angles of inclination of the device and the angular velocity are computed from the accelerometer and the magnetometer measurements using the rotation matrix and quaternions. Although its computation cost is higher, the major advantage of this method is that it reduces the number of singularities to only 2. Furthermore, this method does not require the explicit computation of the angles. The computation process is shown in Fig. 6.

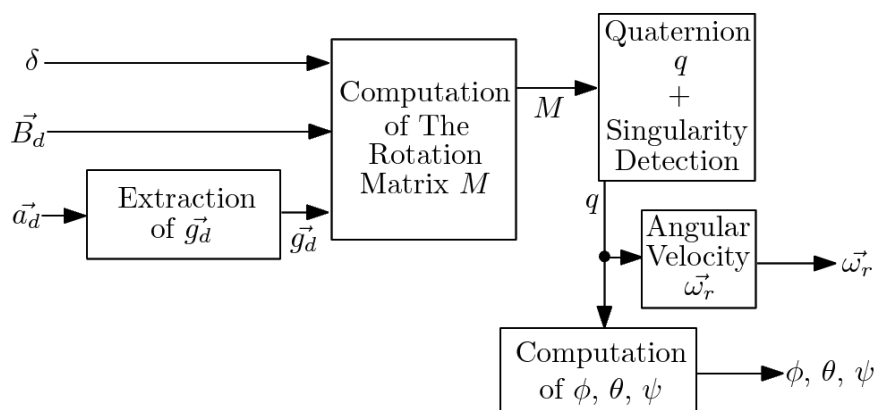


Fig. 6. Computation Process 2.

4.1. Computation of the Rotation Matrix M

Let $\vec{v} = [x \ y \ z]^T$ be a vector. The rotation matrix M transforms \vec{v} into another vector $\vec{v}_r = [x_r \ y_r \ z_r]^T$ by rotating it by an unknown angle α about an unknown axis \vec{a} . The coordinates

of the resulting \vec{v}_f are given by:

$$\vec{v}_f = M \cdot \vec{v} \quad (7)$$

Once \vec{v} and \vec{v}_f are known, it is possible to compute M . Consequently, we will be able to deduce α and \vec{d} .

Let $\vec{g}_{dN} = \frac{\vec{g}_d}{\|\vec{g}_d\|}$ be the normalized gravitational field in the device frame, $\vec{B}_{dN} = \frac{\vec{B}_d}{\|\vec{B}_d\|}$ the normalized magnetic field in the device frame, $\vec{C}_d = \vec{g}_d \times \vec{B}_d$ the cross product between the gravitational field and the magnetic field in the device frame,

$$\vec{C}_{dN} = \frac{\vec{C}_d}{\|\vec{C}_d\|},$$

$$\vec{T}_{Bd} = \vec{B}_{dN} \times \vec{C}_{dN}$$

and

$$\vec{T}_{gd} = \vec{g}_{dN} \times \vec{C}_{dN}.$$

On the other hand, let

$$\vec{g}_{rN} = \frac{\vec{g}_r}{\|\vec{g}_r\|}$$

be the normalized gravitational field in the reference frame,

$$\vec{B}_{rN} = \frac{\vec{B}_r}{\|\vec{B}_r\|}$$

the normalized magnetic field in the reference frame, $\vec{C}_r = \vec{g}_r \times \vec{B}_r$ the cross product between the gravitational field and the magnetic field in the reference frame,

$$\vec{C}_{rN} = \frac{\vec{C}_r}{\|\vec{C}_r\|}, \vec{T}_{Br} = \vec{B}_{rN} \times \vec{C}_{rN}$$

and

$$\vec{T}_{gr} = \vec{g}_{rN} \times \vec{C}_{rN}.$$

The expressions of \vec{g}_{rN} and \vec{B}_{rN} are respectively given by $\vec{g}_{rN} = (0 \ 0 \ 1)^T$ and $\vec{B}_{rN} = (\cos(\theta) \ 0 \ \sin(\theta))^T$. Consequently, $\vec{C}_r = (0 \ g \cdot B \cdot \cos(\theta) \ 0)^T$, $\vec{C}_{rN} = (0 \ 1 \ 0)^T$, $\vec{T}_{Br} = (-\sin(\theta) \ 0 \ \cos(\theta))^T$ and $\vec{T}_{gr} = (-1 \ 0 \ 0)^T$.

The general expression of the matrix M is given by:

$$M = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix}$$

Since $\vec{T}_{ad} = M \cdot \vec{T}_{ar}$, $\vec{C}_{adN} = M \cdot \vec{C}_{arN}$ and $\vec{g}_{adN} = M \cdot \vec{g}_{arN}$, the matrix M can be deduced from \vec{T}_{ad} , \vec{C}_{adN} and \vec{g}_{adN} :

$$M = \begin{bmatrix} -T_{adx} & C_{adNx} & g_{adNx} \\ -T_{ady} & C_{adNy} & g_{adNy} \\ T_{adz} & C_{adNz} & g_{adNz} \end{bmatrix}$$

Since $\vec{T}_{Bd} = M \cdot \vec{T}_{Br}$ and $\vec{E}_{adN} = M \cdot \vec{E}_{arN}$, there is another method, which is to deduce the matrix M from \vec{T}_{Bd} , \vec{C}_{adN} and \vec{E}_{adN} :

$$M = \begin{bmatrix} (E_{adNx} \cdot \cos(\theta) - T_{Bdx} \cdot \sin(\theta)) & C_{adNx} & E_{adNx} \cdot \sin(\theta) + T_{Bdx} \cdot \cos(\theta) \\ (E_{adNy} \cdot \cos(\theta) - T_{Bdy} \cdot \sin(\theta)) & C_{adNy} & E_{adNy} \cdot \sin(\theta) + T_{Bdy} \cdot \cos(\theta) \\ (E_{adNz} \cdot \cos(\theta) - T_{Bdz} \cdot \sin(\theta)) & C_{adNz} & E_{adNz} \cdot \sin(\theta) + T_{Bdz} \cdot \cos(\theta) \end{bmatrix}$$

4.2. Computation of the Quaternion q

Once the matrix M is known, it becomes possible to compute q . The four possible cases are given in Table 2 [1, page 15]. The comparison of M_{11} , M_{22} and M_{33} gives the appropriate case that allows the computation of q .

4.3. Computation of the Angles of Inclination

Once q is known, ϕ , θ and ψ can be computed:

$$\begin{aligned} \phi &= \arctan2 \left(\frac{2 \cdot (q_1 \cdot q_4 + q_2 \cdot q_3)}{1 - 2 \cdot (q_1^2 + q_2^2)} \right) \\ \theta &= \arcsin \left(2 \cdot (q_2 \cdot q_4 - q_3 \cdot q_1) \right) \\ \psi &= \arctan2 \left(\frac{2 \cdot (q_3 \cdot q_4 + q_1 \cdot q_2)}{1 - 2 \cdot (q_2^2 + q_3^2)} \right) \end{aligned}$$

With this method, there are only 2 singularities left: $\theta = \pm \frac{\pi}{2}$. They are known as the gimbal lock. If such a singularity is detected, the previous value of θ is kept.

5. Experimental Results

5.1. Extraction of \vec{g}_d

The Fig. 7 shows the results of the computation of \vec{g}_d . First, the X_d axis has been aligned with the Z_r axis, then the device has been shaken by the user, who created accelerations of about $2g$. Then, the Y_d axis has been aligned with the Z_r axis and, finally, the Z_d axis has been aligned with the Z_r axis.

We can notice that the norm of the extracted gravitational field equals $1g$ and that the highest frequencies due to the fast shakes of the user have been eliminated.

Table 2. Computation of q From M .

| | |
|---|---|
| $M_{22} < -M_{33}$ $M_{11} > M_{22}$ $M_{11} > M_{33}$ | $q = \frac{1}{2} \cdot \begin{pmatrix} \frac{\sqrt{1 + M_{11} - M_{22} - M_{33}}}{[E(M)]_{12} + M_{21}} \\ \frac{[E(M)]_{31} + M_{13}}{\sqrt{1 + M_{11} - M_{22} - M_{33}}} \\ \frac{[E(M)]_{23} - M_{32}}{\sqrt{1 + M_{11} - M_{22} - M_{33}}} \end{pmatrix}$ |
| $M_{22} > M_{33}$ $M_{11} < -M_{22}$ $M_{11} < -M_{33}$ | $q = \frac{1}{2} \cdot \begin{pmatrix} \frac{[E(M)]_{12} + M_{21}}{\sqrt{1 - M_{11} + M_{22} - M_{33}}} \\ \frac{\sqrt{1 - M_{11} - M_{22} - M_{33}}}{[E(M)]_{23} + M_{32}} \\ \frac{[E(M)]_{31} - M_{13}}{\sqrt{1 + M_{11} - M_{22} - M_{33}}} \end{pmatrix}$ |
| $M_{22} < M_{33}$ $M_{11} < -M_{22}$ $M_{11} > M_{33}$ | $q = \frac{1}{2} \cdot \begin{pmatrix} \frac{[E(M)]_{31} + M_{13}}{\sqrt{1 + M_{11} - M_{22} - M_{33}}} \\ \frac{[E(M)]_{23} + M_{32}}{\sqrt{1 + M_{11} - M_{22} - M_{33}}} \\ \frac{\sqrt{1 - M_{11} - M_{22} + M_{33}}}{[E(M)]_{12} - M_{21}} \\ \frac{[E(M)]_{12} - M_{21}}{\sqrt{1 + M_{11} - M_{22} - M_{33}}} \end{pmatrix}$ |
| $M_{22} > -M_{33}$ $M_{11} > M_{22}$ $M_{11} > -M_{33}$ | $q = \frac{1}{2} \cdot \begin{pmatrix} \frac{[E(M)]_{23} - M_{32}}{\sqrt{1 + M_{11} - M_{22} - M_{33}}} \\ \frac{[E(M)]_{31} - M_{13}}{\sqrt{1 + M_{11} - M_{22} - M_{33}}} \\ \frac{[E(M)]_{12} - M_{21}}{\sqrt{1 + M_{11} - M_{22} - M_{33}}} \\ \frac{\sqrt{1 + M_{11} + M_{22} + M_{33}}}{\sqrt{1 + M_{11} - M_{22} - M_{33}}} \end{pmatrix}$ |

5.2. Angular Velocity

Experimental results of the angular velocity computed with our first method virtual gyroscope (top) compared to the one from a real gyroscope (bottom) are given in Fig. 8. The real gyroscope is tied to the accelerometer and the magnetometer and their frames are aligned to get a 9 degree of freedom system. The similarity of the two measures confirms the accuracy of our model.

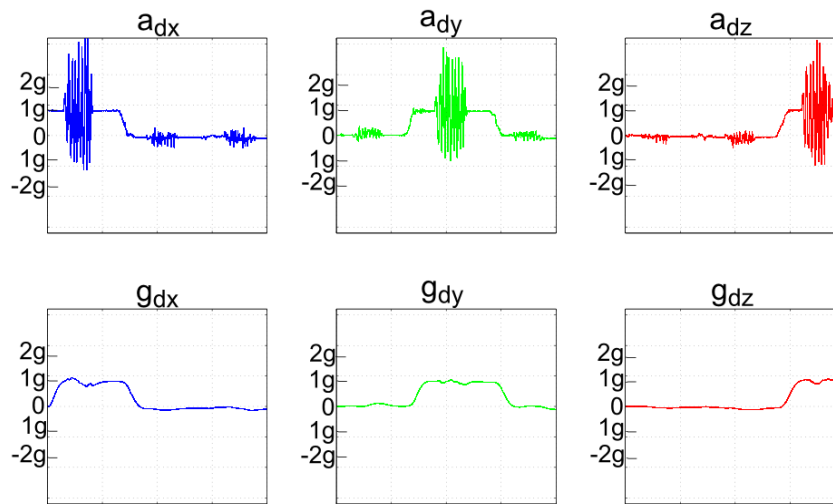


Fig. 7. Extraction of \vec{g} .

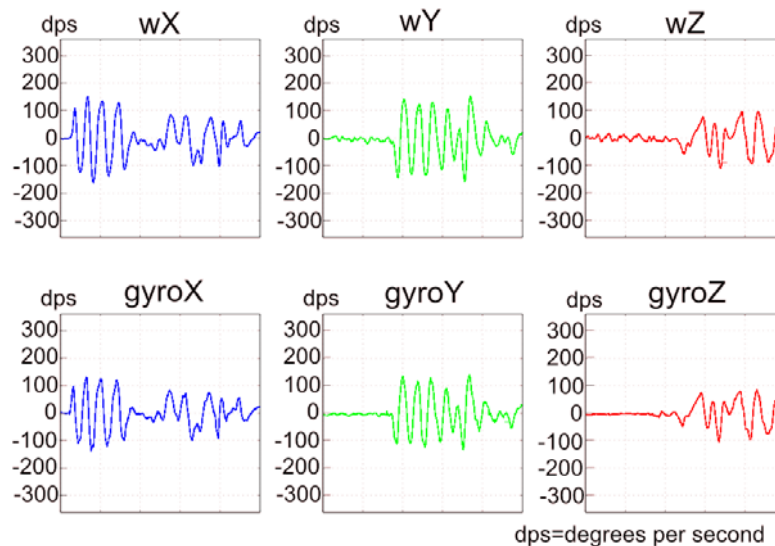


Fig. 8. Angular Velocity Computed with our Virtual Gyroscope (top) vs. a Real one (bottom).

5.3. Virtual Reality Application

In order to evaluate the precision, the latency and finally the usability of our smart sensor we have developed a basic virtual reality application. This application has been developed using OGRE 3D (Object Oriented Graphics Rendering Engine) [9] which is an open source library toolkit. It allows building quickly virtual environment where you can move your view through the control of the camera position. The 3D scene has to be created previously with a classical modeler tool such as 3DS Studio Max or Blender for example. In our implementation, the smart sensor values are used to modify the orientation of the camera or any virtual object of a simulated environment. Hence it replaces the keyboard/mouse. The raw data of the 6 sensors (3 for magnetometer, 3 for accelerometer) are collected by the Freescale MMA9550L hardware (presented in section 2) which forwards these data on a serial over USB connection to the host PC without any processing. Then we implement the equations of section 4 in a processing thread that continuously takes these raw data as input, computes and produces the 3 gyroscope angles as output. Finally these 3 computed values are continuously sent to the OGRE application as shown on Fig. 9.

On the photo of Fig. 10, we can see the sensor board behind the 3D scene computed and displayed in real-time. Moving the board on the 3 axis makes the virtual object (here a model of a plane) moving the same way. This experiment proves the usability of our virtual gyroscope algorithm. Moreover, angles computation can be executed in real-time leading to an almost instantaneous interaction with the virtual environment.

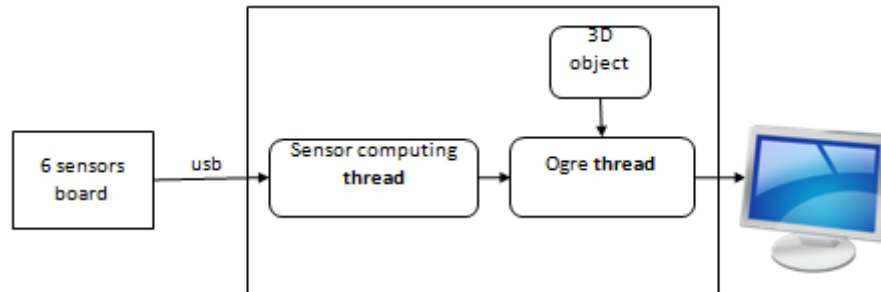


Fig. 9. Software architecture.

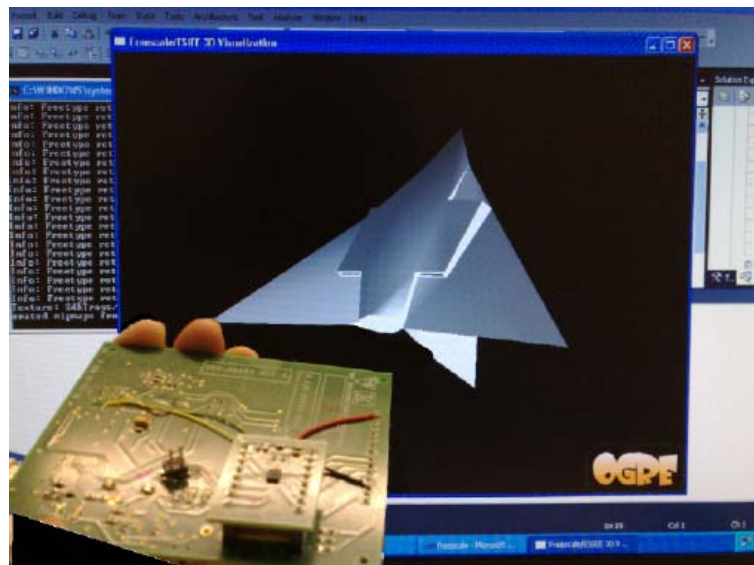


Fig. 10. Software architecture.

6. Conclusion and Future Works

In this paper, we have presented two methods to implement a virtual gyroscope that only uses the measurements of an accelerometer and a magnetometer, with 6 degrees of freedom.

The two methods have their own advantages and drawbacks. The method which uses the angles of inclination is easier to implement, but there are 8 singularities, which need to be solved. Moreover, the computation of ψ depends on the computation of θ , which in turns depends on ϕ . If there is a singularity on ϕ , the computation of the angles is not possible. On the other hand, the method with the rotation matrix has only two singularities but its computation cost is higher. The second method has not been completely implemented and validated yet; this is our current work.

The precision of both methods and their limitations must be investigated and will be our main future work.

Finally, we plan to optimize the implementation of both methods on the MMA9550L. This will allow us to provide the angular velocity and the angles of inclination of the device and use them for several applications, like a 3-dimensional mouse, a virtual joystick, a human motion tracker. The MMA9550L board can communicate with the PC with a Bluetooth connection. Consequently, the board can become a portable device with its own power supply.

Acknowledgment

The authors would like to thank Freescale for their support, the platform, and Mr. Mark Pedley whose work is the base of this project.

References

- [1]. J. Diebel, Representing attitude: Euler angles, unit quaternions, and rotation vectors. Technical Report, *Stanford University*, California 94301-9010, October 2006.
- [2]. T. Liu, G. -R. Zhao, and S. Pan, New calculating method of angular velocity in gyroscope-free strapdown inertial navigation systems, *Systems Engineering and Electronics*, 32, 1, January 2010, pp. 162–165.
- [3]. P. Schopp, L. Klingbeil, C. Peters, A. Buhmann, and Y. Manoli, Sensor fusion algorithm and calibration for a gyroscope-free IMU, in *Proceedings of the Eurosensors 23rd Conference*, Vol. 1, 2009, pp. 1323–1326.
- [4]. A. L. Schwab, Quaternions, finite rotation and Euler parameters, 2002.
- [5]. D. Stahlke, Quaternions in classical mechanics, 2007.
- [6]. C. Wang, J.-X. Dong, S.-H. Y., and X.-W. Kong, Hybrid algorithm for angular velocity calculation in a gyroscope-free strapdown inertial navigation system, *Journal of Chinese Inertial Technology*, 18, 4, 2010, pp. 401–404.
- [7]. X.-N. Wang, S.-Z. Wang, and H.-B. Zhu, Study on models of gyroscope-free strap-down inertial navigation system, *Binggong Xuebao/Acta Armamentarii*, 27, 2, 2006, pp. 288–292.
- [8]. J. R. Wertz, Spacecraft Attitude Determination and Control, *D. Reidel Publishing Company*, Dordrecht, Holland, 1978.
- [9]. <http://www.ogre3d.org>

2012 Copyright ©, International Frequency Sensor Association (IFSA). All rights reserved.
(<http://www.sensorsportal.com>)

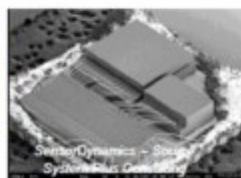
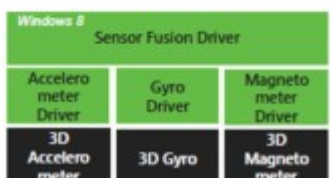
Inertial Combo Sensors for Consumer & Automotive

Technology, Applications, Industry & Market Report to 2016



This report is focused on the analysis of the opportunities and the challenges for inertial combo sensors in those high-volume market areas.

http://www.sensorsportal.com/HTML/Inertial_Combo_Sensors_Market.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 of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor 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. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

Topics Covered

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

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

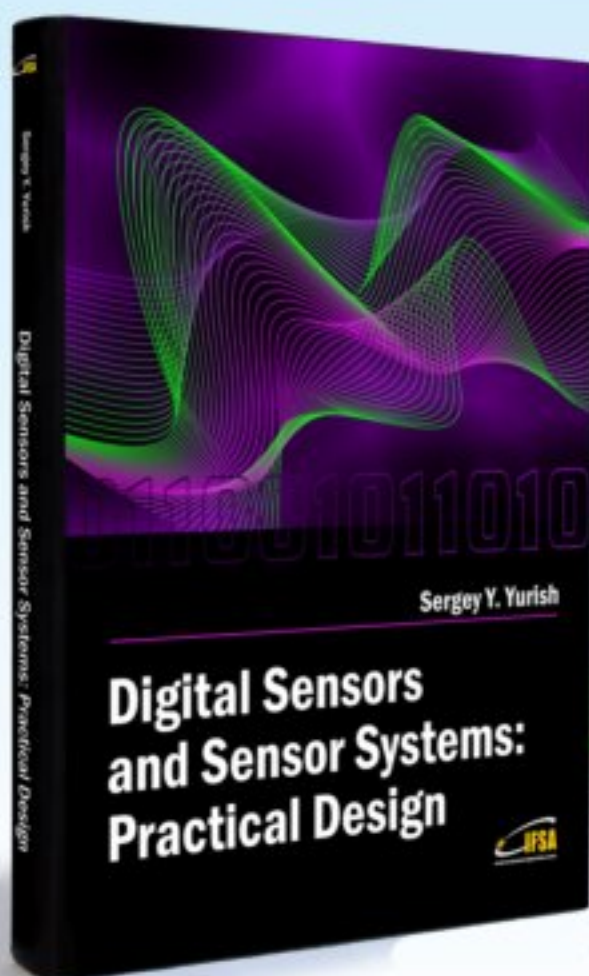
Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: <http://www.sensorsportal.com/HTML/DIGEST/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_2012.pdf

Digital Sensors and Sensor Systems: Practical Design will greatly benefit undergraduate and at PhD students, engineers, scientists and researchers in both industry and academia. It is especially suited as a reference guide for practitioners, working for Original Equipment Manufacturers (OEM) electronics market (electronics/hardware), sensor industry, and using commercial-off-the-shelf components, as well as anyone facing new challenges in technologies, and those involved in the design and creation of new digital sensors and sensor systems, including smart and/or intelligent sensors for physical or chemical, electrical or non-electrical quantities.



"It is an outstanding and most completed practical guide about how to deal with frequency, period, duty-cycle, time interval, pulse width modulated, phase-shift and pulse number output sensors and transducers and quickly create various low-cost digital sensors and sensor systems ..." (from a review)

Order online:

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



www.sensorsportal.com