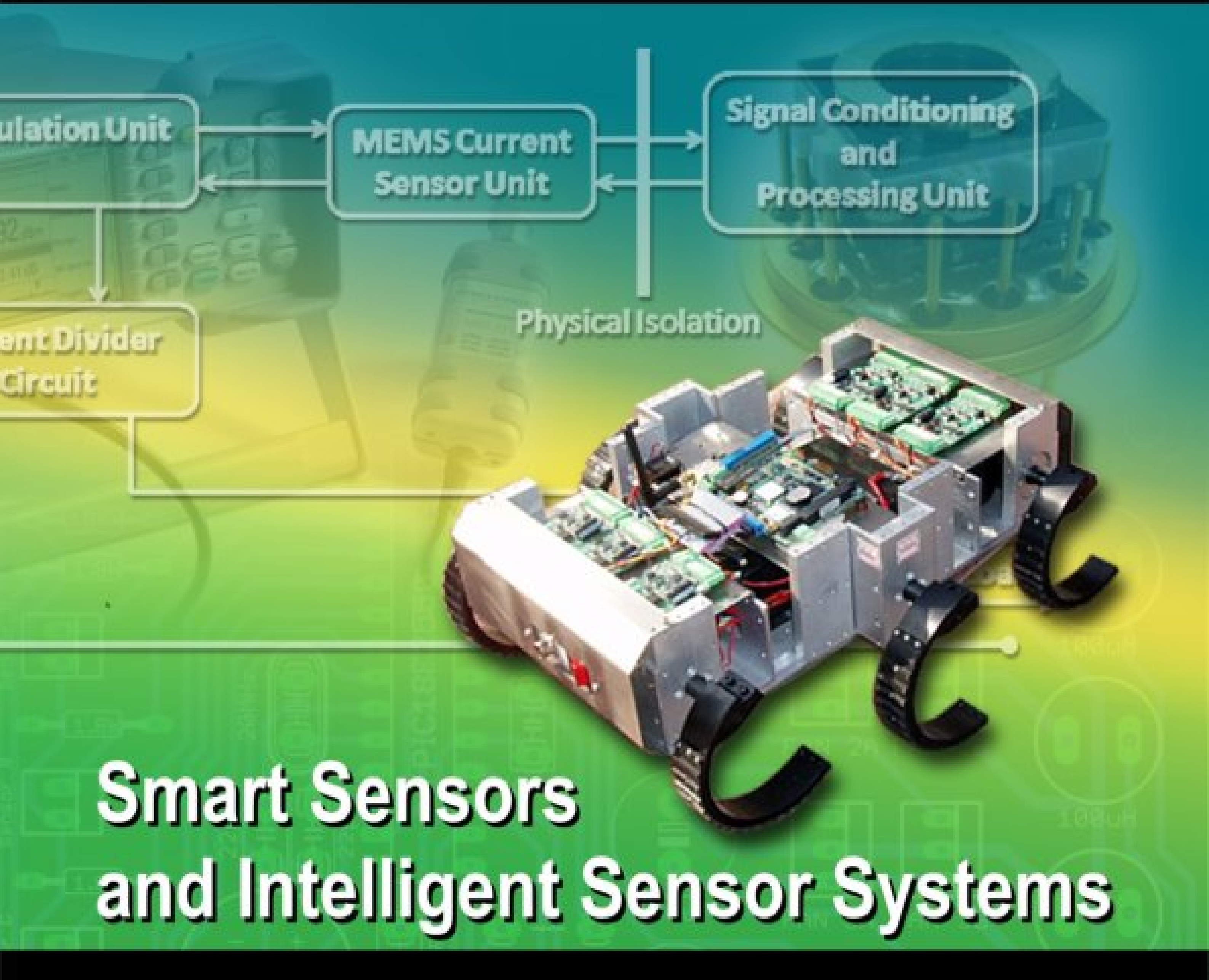
ISSN 1726-5479

SENSORS & TRANSDUCERS

3/12 vol. 138



Smart Sensors and Intelligent Sensor Systems

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 138, Issue 3, March 2012 | www.sensorsportal.com | ISSN 1726-5479

Editors-in-Chief: professor Sergey Y. Yurish, tel.: +34 696067716, e-mail: editor@sensorsportal.com

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

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

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

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

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

Editor for Africa
Maki K.Habib, American University in Cairo, Egypt

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

Editorial Advisory Board

Abdul Rahim, Ruzairi, Universiti Teknologi, Malaysia
Ahmad, Mohd Noor, Nothern University of Engineering, Malaysia
Annamalai, Karthigeyan, National Institute of Advanced Industrial Science and Technology, Japan
Arcega, Francisco, University of Zaragoza, Spain
Arguel, Philippe, CNRS, France
Ahn, Jae-Pyoung, Korea Institute of Science and Technology, Korea
Arndt, Michael, Robert Bosch GmbH, Germany
Ascoli, Giorgio, George Mason University, USA
Atalay, Selcuk, Inonu University, Turkey
Atghiaee, Ahmad, University of Tehran, Iran
Augutis, Vygantas, Kaunas University of Technology, Lithuania
Avachit, Patil Lalchand, North Maharashtra University, India
Ayesh, Aladdin, De Montfort University, UK
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
Granel, Annette, Goteborg University, Sweden
Graff, Mason, The University of Texas at Arlington, USA
Guan, Shan, Eastman Kodak, USA
Guillet, Bruno, University of Caen, France
Guo, Zhen, New Jersey Institute of Technology, USA
Gupta, Narendra Kumar, Napier University, UK
Hadjiloucas, Sillas, The University of Reading, UK
Haider, Mohammad R., Sonoma State University, USA
Hashsham, Syed, Michigan State University, USA
Hasni, Abdelhafid, Bechar University, Algeria
Hernandez, Alvaro, University of Alcala, Spain
Hernandez, Wilmar, Universidad Politecnica de Madrid, Spain
Homentcovschi, Dorel, SUNY Binghamton, USA
Horstman, Tom, U.S. Automation Group, LLC, USA
Hsiai, Tzung (John), University of Southern California, USA
Huang, Jeng-Sheng, Chung Yuan Christian University, Taiwan
Huang, Star, National Tsing Hua University, Taiwan
Huang, Wei, PSG Design Center, USA
Hui, David, University of New Orleans, USA
Jaffrezic-Renault, Nicole, Ecole Centrale de Lyon, France
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
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, Sihua, Agiltron, Inc., USA
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, 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
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
Passaro, Vittorio M. N., Politecnico di Bari, Italy
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
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
Raoof, 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, Bhbha Atomic Research Centre, Mumbai, India
Schneider, John K., Ultra-Scan Corporation, USA
Sengupta, Deepak, Advance Bio-Photonics, India
Seif, Selemani, 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, University of Toledo, USA
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 Comp. Technol. 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, Industr. 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
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, 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

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and on CD. Copyright © 2012 by International Frequency Sensor Association. All rights reserved.

Contents

Volume 138
Issue 3
March 2012

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Automotive Pressure Sensor (White Paper)
Ninghai Sendo International Trading Co., Ltd. 1

A Novel MEMS Based Current Sensor Design for Smart Grid Applications
A. Venkateswaran, A. Amalin Prince.................... 3

Application of Frequency-Domain Integral Algorithm to the Processing of Sport Signals Based on MTi Sensor
Qian Yu, Yunjian Ge, Tingting Ma, Zeyuan Lu.................... 14

A Compact X-ray Spectrometer Using Silicon Drift Detector
M. Shanmugam, Y. B. Acharya, V. Mishra, P. N. Patel, S. K. Goyal 22

Virtual Instrumentation with Application in Multiaxial Extensometric Force Platform
André Guimarães Oliveira and Alexandre Balbinot.................... 35

Measurement of Bubble Flow in Liquid Using Optical Tomography
Naizatul Shima Mohd Fadzil, Siti Zarina Mohd Muji, Ruzairi Abdul Rahim, Yusri Mohd Yunus, Salinda Bunyamin, Shafishuaza Sahlan, Nor Muzakkir Nor Ayob.................... 50

Evaluation of Online Strain Monitoring of Concrete/Steel Structures - Laboratory and Field Studies
M. S. Karthikeyan, A. K. Parande, K. Kumar, R. Jeyaram, N. Palaniswamy, A. Sivashanmugam, R. H. Suresh Bapu, K. Lakshmibarani and C. Ponraj.................... 59

Applications of Angular Measurement Using Hit or Miss Transform
N. S. Abinaya, V. R. Priya and S. Rakesh Kumar.................... 71

Design of Cursor Magnets on the Wiedemann Effect in Magnetostrictive Linear Position Sensors
Yong-Jie Zhang, Chun-Feng L. V., Jin-Feng Yang, Wei-Wen Liu, Hui Zhao.................... 80

Data Acquisition Latency in Dynamic Localization: A Weighted Least Squares Approach
Mohammad Amin Rahimian, Shinji Ohyama 88

Stability Analysis and Design of PI Controller Using Kharitnov Polynomial for Rotary Inverted Pendulum
Jim George, Bipin Krishna, V. I. George, Shreesha C., Mukund Kumar Menon 104

Energy Harvesting Via Pyroelectric Transducer
Ashok Batra, Sudip Bhattacharjee, Aswith Chilvery and Jason Stephens.................... 114

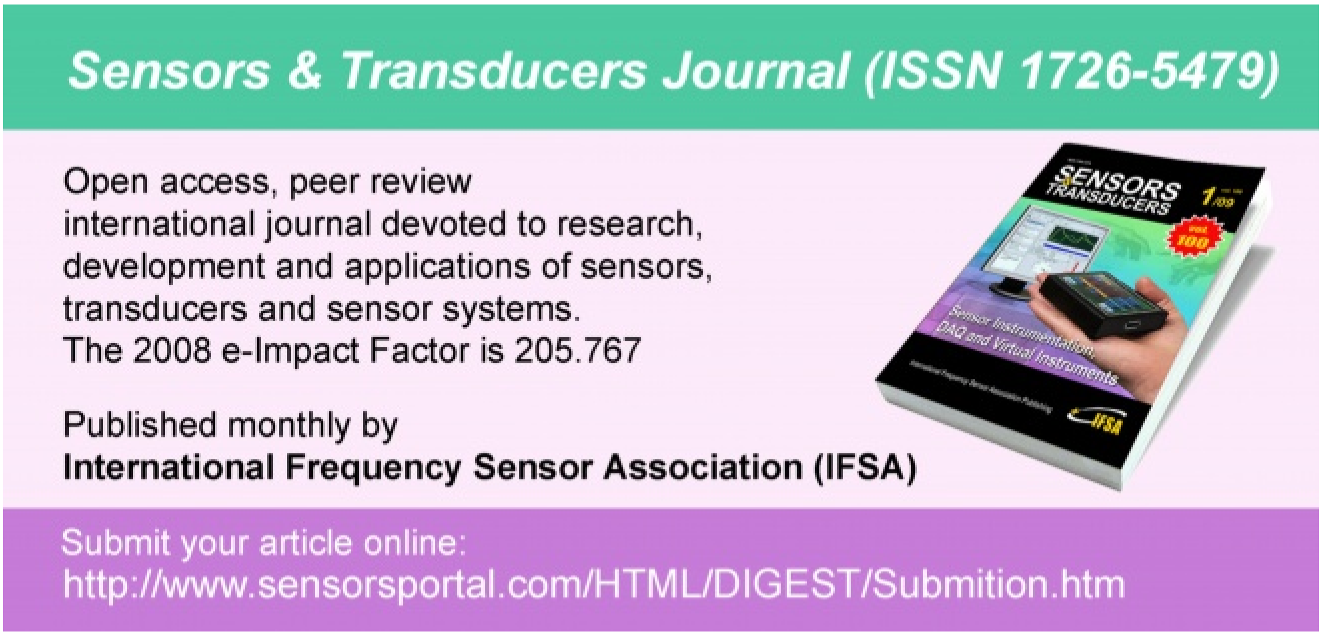
Dynamic Control of Hexapod Robot Based on Plantar Pressure Sensor
Yong FENG, Yunjian GE, Yan Huang.................... 122

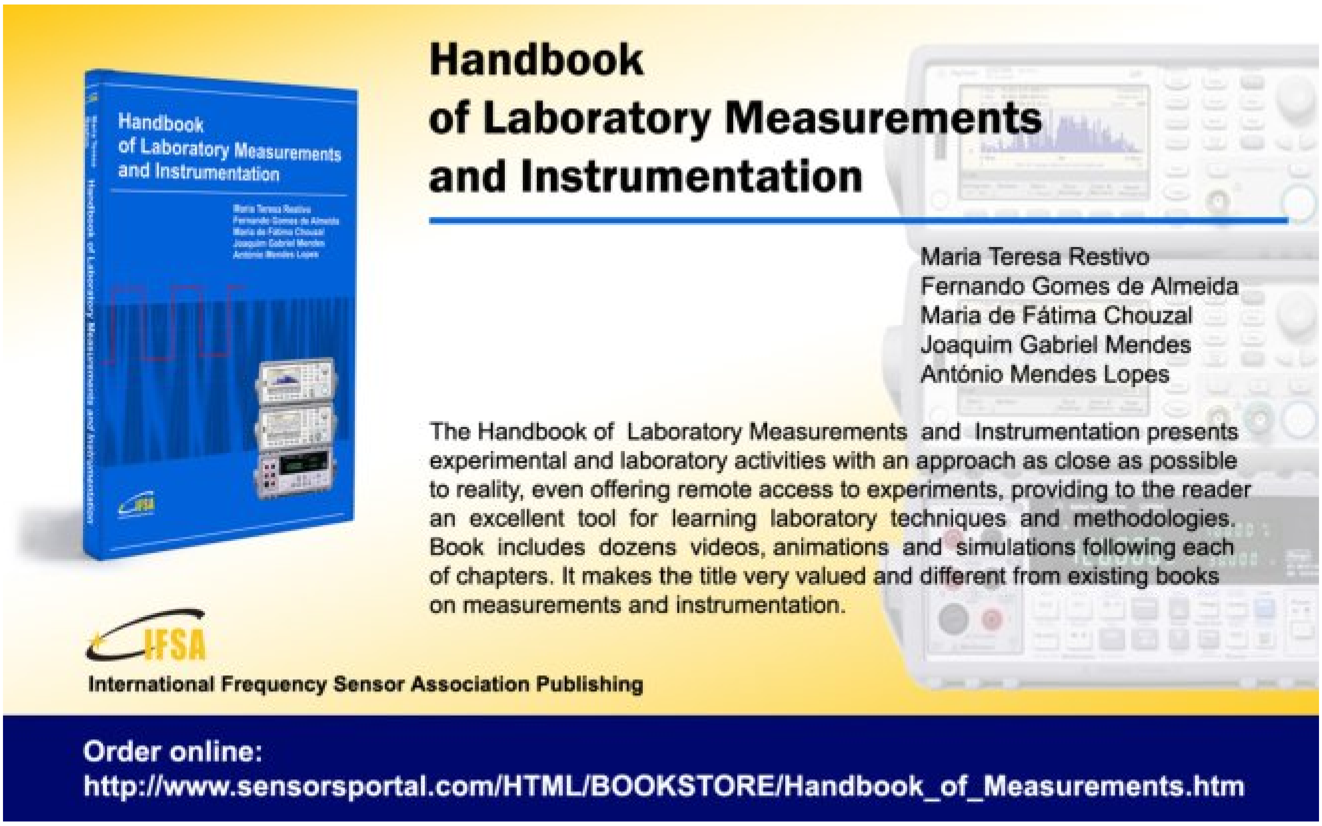
Study on Speed Adaptation Control for a Gait Rehabilitation Training Robot
Yongjiu Liu, Buyun Wang, Guangbin Zhang, Tingting Ma, Feng Shuang and Quanjun Song.. 132

Stochastic Filters for Mobile Robot SLAM Problems - A Review
K. Ramkumar, N. S. Manigandan... 141

Authors are encouraged to submit article in MS Word (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com
Please visit journal's webpage with preparation instructions: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm

International Frequency Sensor Association (IFSA).





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.iaria.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.iaria.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.iaria.org/conferences2012/CENICS12.html

Sensors & Transducers Journal, Vol. 138, Issue 3, March 2012, pp. 122-131

Sensors & Transducers

ISSN 1726-5479
© 2012 by IFSA
http://www.sensorsportal.com

Dynamic Control of Hexapod Robot Based on Plantar Pressure Sensor

[1,2] Yong FENG, [2]Yunjian GE, [3]Yan Huang

[1] Department of Automation, University of Science and Technology of China
Hefei, Anhui, 230026, China

[2] Robot Sensor and Human-Machine Interactive Laboratory, Institute of intelligent Machine, Chinese Academy of Science, Hefei, Anhui, 230031, China

[3] Training Base, Electronic Engineering Institute of People's Liberation Army, Hefei, Anhui,230031, China

[1] Tel.: +86-551-5591194

[1]E-mail: fengyong@mail.ustc.edu.cn

Received: 3 January 2012 /Accepted: 20 March 2012 /Published: 31 March 2012

Abstract: This paper proposed a hexapod control method based on plantar pressure and designed the plantar pressure acquisition system. The experiments verified that the designed plantar pressure sensor can measure the dynamic plantar pressure accurately in real-time and the control method using plantar pressure can make the hexapod robot run stably with long time in different terrain condition.
Copyright © 2012 IFSA.

Keywords: Plantar pressure sensor, Hexapod robot, Dynamic control, Spring-loaded inverted pendulum.

1. Introduction

During the last decade there has been growing interest in the application of legged robot because the mobility of legged robots in the widest variety of terrain conditions is better than that of wheeled, tracked or railed robots. Hexapod robot is an important kind of legged robot which has the features of high energy efficiency and motion speed, for example, RHex can travel more than one body length per second based on autonomous energy [1].

Control method based on Bipedal Spring-Loaded Inverted Pendulum (BSLIP) is a dynamic control method of six legged robot, this control method force the true high dimensional system dynamics down onto the lower dimensional subspace corresponding to the BSLIP template. It improves substantially the maneuverability and dynamic range of six legged robot behaviors relative to the initial prototype open-loop algorithms [2]. The force of the system is acted through the legs which are on stance phase and it is the key to dynamic controller and it is often used to compute the states of legs and determine the boundaries of related two phases [3]. But how to acquire the force acted on the legs was not discussed in [2-4]. Considering all the force acted on the body is acted by legs and gravity, the gravity can be counted to a const, but the force acted by legs is related to time. If the force acted on legs acted by ground can be acquired, it will be helpful for the controlling of hexapod robot.

The goal of this paper is to design the plantar pressure sensor for measuring the force acted on the legs and design the dynamic controller based on BSLIP.

2. Hexapod Robot Model

2.1. The Structure of Hexapod Robot and Coordinates

The planar hexapod robot is depicted in Fig. 1, it consists of rigid body with six compliant legs, and each leg possessing only one independently actuated revolute degree of freedom. The attachment points of the legs are all fixed relative to the body symmetrically. The "virtual leg" is defined as the leg extending from the body center of mass to a stationary point on the ground [2]. The mass and inertia of the body are m and I respectively, the total mass of six legs $m_t << m$.

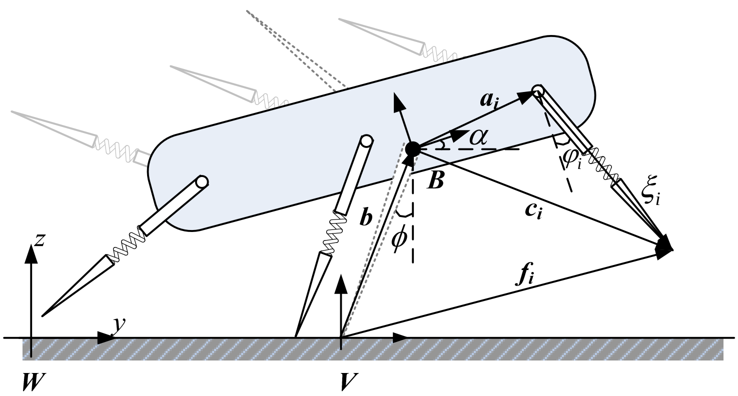


Fig. 1. Hexapod robot model.

We define three reference frame: W as the fixed inertial world frame, V as the virtual toe frame with the same orientation as W, but located at the foot of virtual leg, and finally B as the body frame, affixed to the center of the mass of the system. The position and orientation of the body are represented by a body-fixed frame B with respect to an inertial world frame W. The orientation of B determines the body pitch α and is also expressed by the rotation matrix ${}^W_B R$. The position of the body in V is denoted by b. The position of the toe is fixed on the ground and is denoted by f_i. Each leg is attached to the body through a pin joint with an independently controllable torque τ_i, located at a_i in the body coordinates B. Each leg is composed of a radial spring with stiffness k_i and incorporates viscous damping with coefficient d_i.

The toe position c_i defined with respect to V frame is:

$$c_i = f_i - b \tag{1}$$

If the toe position c_i is defined with respect to B frame:

$$c_i = a_i + \xi_i \tag{2}$$

Rotation matrix ${}^{W}_{B}R$ and ${}^{B}_{W}R$ are the functions of α :

$$ {}^{W}_{B}R = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \tag{3}$$

$$ {}^{B}_{W}R = {}^{B}_{W}R^{T} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \tag{4}$$

According to B frame, ξ_i can be defined as:

$$\xi_i = {}^{B}_{W}R \cdot (f_i - b) - a_i = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \cdot \begin{bmatrix} f_{iy} - b_y \\ f_{iz} - b_z \end{bmatrix} - \begin{bmatrix} a_{iy} \\ a_{iz} \end{bmatrix} \tag{5}$$

Because a_i is a constant with respect to B frame, then we can obtain:

$$\dot{\xi}_i = \begin{bmatrix} -\sin\alpha & \cos\alpha \\ -\cos\alpha & -\sin\alpha \end{bmatrix} \cdot \begin{bmatrix} f_{iy} - b_y \\ f_{iz} - b_z \end{bmatrix} \dot{\alpha} + \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \cdot \begin{bmatrix} \dot{f}_{iy} - \dot{b}_y \\ \dot{f}_{iz} - \dot{b}_z \end{bmatrix} \tag{6}$$

The polar coordinates of ξ_i is defined as:

$$\xi_i = [\rho_i \quad \varphi_i]^T = \left[\sqrt{\xi_{iy}^2 + \xi_{iz}^2} \quad \arctan(\xi_{iy} / \xi_{iz})\right]^T \tag{7}$$

Derivative of ρ_i and φ_i with respect to time, we get:

$$\dot{\rho}_i = \frac{\xi_{iy}\dot{\xi}_{iy} + \dot{\xi}_{iy}\xi_{iy}}{\sqrt{\xi_{iy}^2 + \xi_{iz}^2}} \tag{8}$$

$$\dot{\varphi}_i = \frac{\xi_{iy}\dot{\xi}_{iz} - \dot{\xi}_{iy}\xi_{iz}}{\xi_{iy}^2 + \xi_{iz}^2} \tag{9}$$

2.2. Dynamic Equation

The configuration of the leg consists of stance phase and swing phase, in stance phase the leg contacts with the ground, in swing phase the leg does not contact with the ground. Six binary flags

$s_i \in \{0,1\}\ (i = 1,2,\cdots,6)$ denote the leg configuration, 0 states that the leg touches the ground whereas 1 states that the leg is in flight.

The forces generated by the legs arise from their radial compliance and damping as well as the hip torques. The radial force component of i th leg can be formulated as follows:

$$F_{ri} = -k_i(\rho_{i0} - \rho_i) - d_i\dot{\xi}_i\,, \tag{10}$$

where ρ_{i0} is the spring rest length of i th leg.

As a result, i th leg force acted on the ground can be written as:

$$F_i = {}_B^W R(\alpha + \varphi_i)\begin{bmatrix} \tau_i / \rho_i \\ -F_{ri} \end{bmatrix} = \begin{bmatrix} \cos(\alpha + \varphi_i) & -\sin(\alpha + \varphi_i) \\ \sin(\alpha + \varphi_i) & \cos(\alpha + \varphi_i) \end{bmatrix} \cdot \begin{bmatrix} \tau_i / \rho_i \\ -F_{ri} \end{bmatrix} \tag{11}$$

Where τ_i / ρ_i is the force component which is orthogonal to the radial orientation of leg.

Defining the force and torque vector acted on six legs:

$$F_r = [F_{r1}, \cdots, F_{r6}] \tag{12}$$

$$\tau = [\tau_1, \cdots, \tau_6] \tag{13}$$

Neglecting the Coriolis force and centrifugal force of the system, the dynamic equation of the system under the influence of external forces generated by the legs take the form:

$$m(\ddot{b} + g) = \sum_{i=1}^{6} s_i F_i \tag{14}$$

$$I\ddot{\alpha} = \sum_{i=1}^{6} s_i (f - b_i) \times F_i \tag{15}$$

Because the toe is fixed to the ground in the stance phase, the dynamic equation of the each leg is as the follow when neglecting the gravity:

$$m_t \ddot{f}_i = (1 - s_i)F_i = (1 - s_i) \cdot {}_B^W R(\alpha + \varphi_i) \cdot \begin{bmatrix} \tau_i / \rho_i \\ -F_{ri} \end{bmatrix} \tag{16}$$

3. Controller Based on BSLIP

3.1. Bipedal Spring-Loaded Inverted Pendulum (BSLIP) model

According to [3], in attempt to capture the characteristic features of the hexapod robot control we simplify the system to a Bipedal Spring-Loaded Inverted Pendulum (BSLIP) model, illustrated in Fig. 2.

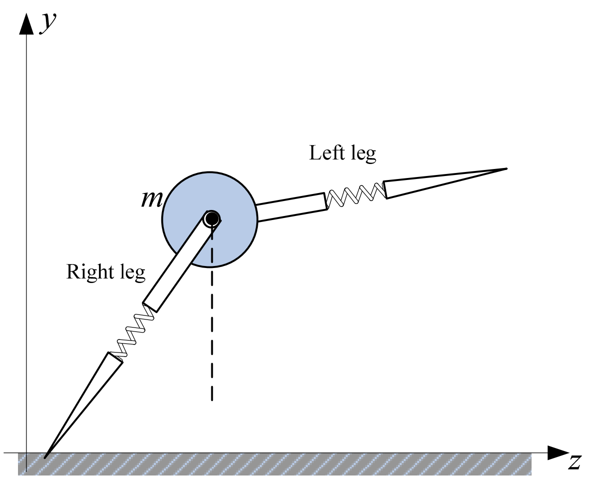


Fig. 2. BSLIP model.

The BSLIP model consists of a point mass m, attached to two compliant massless legs labeled as left and right which can freely rotate around the hip joint [3]. Each leg has two possible discrete modes: stance and swing. Throughout the stance phase of a leg its toe is fixed on the ground and the body is acted upon by the associated spring and damping forces. When the leg is in swing phase, it does not affect the body dynamics.

In the motion of hexapod robot, six legs are divided into two groups named left tripod and right tripod, the left tripod consist of front leg and rear leg in the left side and the middle leg in the right side of the body, the right tripod consist of the rest of legs. We assume that the left tripod and right tripod is always parallel during stance period and flight period. The two tripods are treated as the two virtual legs (Fig. 1) of the BSLIP model, so the control problem of hexapod can be treated as the control of the BSLIP model.

The BSLIP system has four modes: left stance, right stance, double stance and flight, determined by which legs are in contact with the ground. The dynamic characteristic of the system in different modes are different, and the control laws are different in different modes. How to identify the transitions between two modes is important, reference [3] and [4] use threshold functions respect to leg length and height of the body, the value of threshold functions determine the mode. But it is difficult to measure the height of the body in practice. We use the force $\overline{F_i}$ $(i = 1,2)$ acted on the toe to identify the mode, then transitions between modes are governed by transition diagram illustrated in Fig. 3.

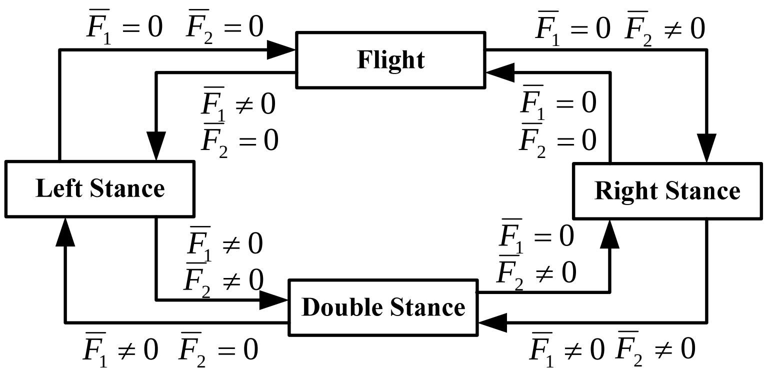


Fig. 3. Mode transition of BSLIP model.

3.2. Hexapod Robot Control Based on BSLIP Model

The design principle of the controller based on BSLIP for hexapod robot is to choose proper hip controls τ to bring the motion of the body as close as possible to the trajectories of the BSLIP [5]. Towards this end, the approach entails the followed separate components:

(1) Imposing desired angles of two alternating tripods.

(2) Determining the appropriate torque controls to tune the dynamics of the body during stance phase.

(3) The coordination and control of the swing tripod.

The desired angles of two tripods is to ensure the stability of the tripod gait, we define the desired set of desired angles and times as:

$$\Phi^* = \{t_s^*, t_f^*, \varphi_s^*, \varphi_f^*\} \tag{17}$$

Where, t_s^* and t_f^* are the time when the leg is in stance phase and flight phase respectively, φ_s^* and φ_f^* are the angle of the leg when it is during the phase of stance and flight respectively.

Assume the actual angles and times as:

$$\Phi = \{t_s, t_f, \varphi_s, \varphi_f\} \tag{18}$$

The goal of the control is to acquire the torque of the hip to track the desired reference signal Φ^*. The errors of the angle during two phases are:

$$e_s = \varphi_s - \varphi_s^* \tag{19}$$

$$e_f = \varphi_f - \varphi_f^* \tag{20}$$

Propotional-derivative (PD) control algorithm is assigned to obtain the desired velocity to track the desired angle, the desired velocity take the form:

$$\omega_{sd} = k_{ps} e_s + k_{ds} \dot{e}_s \tag{21}$$

$$\omega_{fd} = k_{pf} e_f + k_{df} \dot{e}_f \tag{22}$$

Where proportional coefficient (k_{ps} and k_{pf}) and derivative coefficient (k_{ds} and k_{df}) values are determined by using the trial and error method.

During swing phase the torque acted on the leg can be determined by:

$$\tau_f = m_t \xi_0 \dot{\omega}_{fd} \tag{23}$$

The pitch α will be a const when the three legs in a tripod keeps parallel during stance period, then the dynamic equation is determined only by (14). Assuming that the actual force acted on the toe of the leg by ground is $\overline{F}_r$, then the length of the leg can be estimated by:

$$\hat{\xi} = \overline{F}_r / k \tag{24}$$

Form (14) we can derive the component orthogonal to the radial orientation of leg:

$$m(\ddot{b}_\tau + g_\tau) = F_\tau , \tag{25}$$

where $b_\tau = \hat{\xi}\cos\varphi$, $g_\tau = g\sin\phi = g\sin(\varphi - \alpha)$.

Then we can obtain the desired torque during stance phase:

$$\tau_s = m(\ddot{b}_{\tau d} + g_\tau)\hat{\xi} , \tag{26}$$

where $b_{\tau d}$ is the desired height of the body, and it can be derived from the followed equation:

$$b_{\tau d} = \hat{\xi}\cos\varphi_{sd} = \frac{\overline{F}_r}{k}\cdot\cos\varphi_{sd} \tag{27}$$

The force $\overline{F}_r$ is measured by force sensor fixed on the toe of the leg.

4. The Design of Force Sensor

The plantar pressure signal acquisition system consists of two parts: pressure sensor device, data acquisition circuit.

4.1. Collection of Sensor Model

The FlexiForce A201 Sensor was (Tekscan, Inc., USA) used to measure plantar pressure. Because the sensor is small, flexible and thin, the hexapod robot gait is not affected. The sensing area size of the sensor is 14 mm×14 mm×0.203 mm, and the pressure-sensitive area of the sensor is a 9.53-mm-diameter circle [6]. In the process of measurement the sensor's data was input to central control computer embedded in the robot through data acquisition card. Every sensor in different leg is numbered, so we can figure out the pressure of different leg through the sensors number. The sampling frequency can be set before experiment.

4.2. Design of Data Acquisition Circuit

Data acquisition circuit consists of signal condition circuit and signal acquisition model. The role of condition circuit is to transfer the current to voltage, we use surface mounted operational amplifier with low temperature drift and resistance in order to reduce the dimension of the device and improve the accuracy of the transition. The condition circuit is showed in Fig. 4, where R_1 is the sensor model with full-loaded resistance value 20 $\text{k}\Omega$, R_2 is surface mounted resistance which resistance value is 20 $\text{k}\Omega$, operational amplifier is MC34074 and its output is $V_{out} = 5V \times (\frac{R_2}{R_1})$. The voltage of the output is in the field of $0 \sim 5V$. R_3 and C_3 is a low-pass filter to filter high frequency noise.

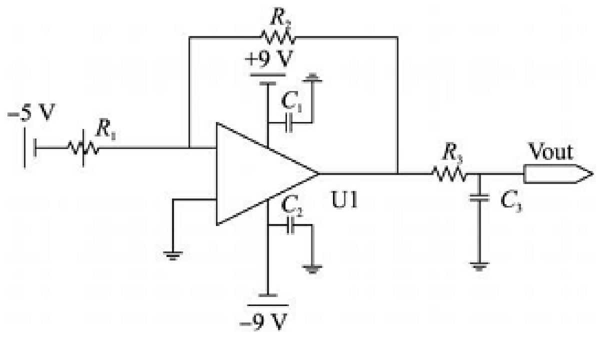


Fig. 4. Data acquisition circuit.

USB-4750 [7] (Advantech Inc., China) is used to acquire the output signal from data acquisition circuit.

4.3. Data Processing

The output of the force sensor device will be disturbed by noise, it is necessary to remove the noise from the data. The pressure signal during normal working is low-frequency signal and its amplitude is large, but the noise is high-frequency and its amplitude is small. Wavelet transform is a time-frequency analysis method [8], it has been widely used in the fields of signal denoising. In our experiments, we used Daubechie 4 (db4) wavelet, and the decomposition level was experimentally set to 4. Original data comparison with filtered data were showed in Fig. 5 (the blue line is original signal, and the red line is filtered signal). It is obvious that the noise has been filtered mostly.

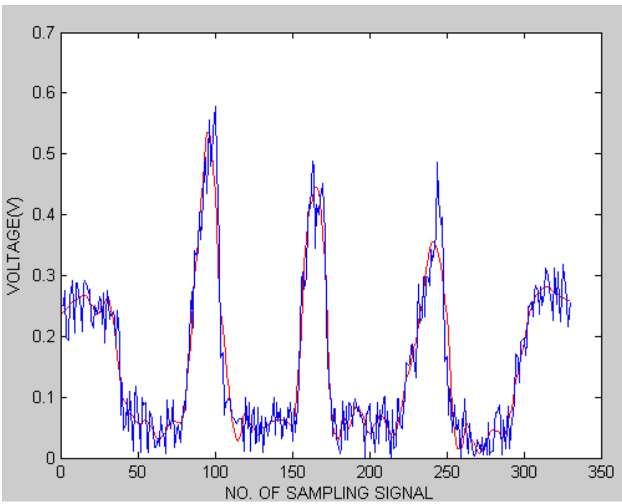


Fig. 5. Original data comparison with filtered data.

5. Experiment and Result

We designed a hexapod robot (see Fig. 6.), it consists of a rigid body and six C shaped legs. Each leg has a one revolute degree freedom and is driven by a DC motor. Power is provided by 24 V batteries. On-board computation is performed by a PC104 with 416 MHz running WinCE5.0 real-time OS. The control program is coded in Embedded Visual C4.0. The planar press sensor device is fixed on the toe of each leg.

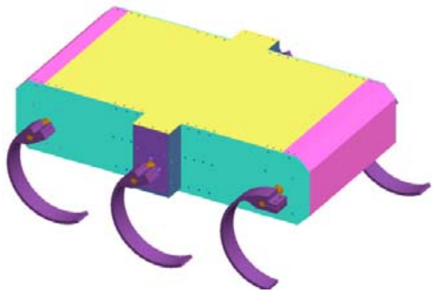


Fig. 6. Hexapod robot experiment platform.

The experiment was done in three types of terrain condition which are flat ground, grassplot and slope (see Fig. 7.). In order to compare the performance of the proposed control method we use two control methods, one is PD control method without force sensor and the other is proposed control method. The experimental results showed that the gait stability will deteriorate when the robot locomotion in long time especially in grassplot. But the locomotion performance improved largely used the proposed method, it can locomotion stably in long time in different terrain condition.

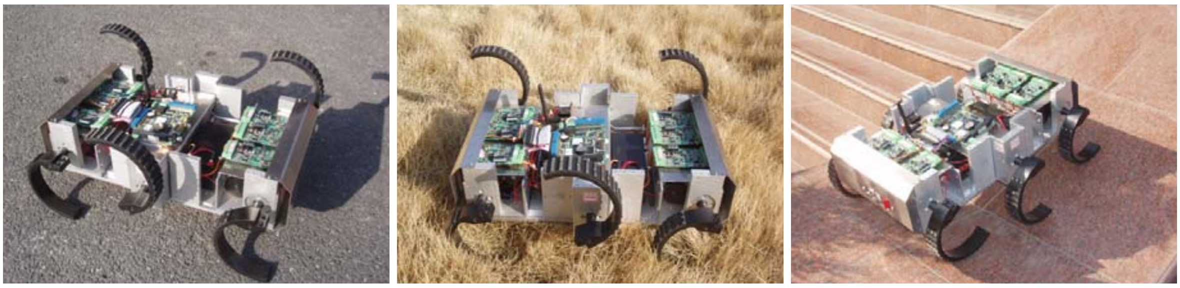


Fig. 7. Experiment of hexapod robot.

6. Conclusions

Hexapod robot has high locomotion performance comparing with wheeled and track robot. In this paper we proposed a novel control method based on planar pressure sensor. We designed the hexapod robot platform inspired by RHex and designed the planar pressure information acquisition system. The pressure collected from the sensor can be used to estimate the state of the robot and help to control the robot. Experimental results showed that the proposed method can make the hexapod robot locomotion stably in long time in different situation.

Acknowledgements

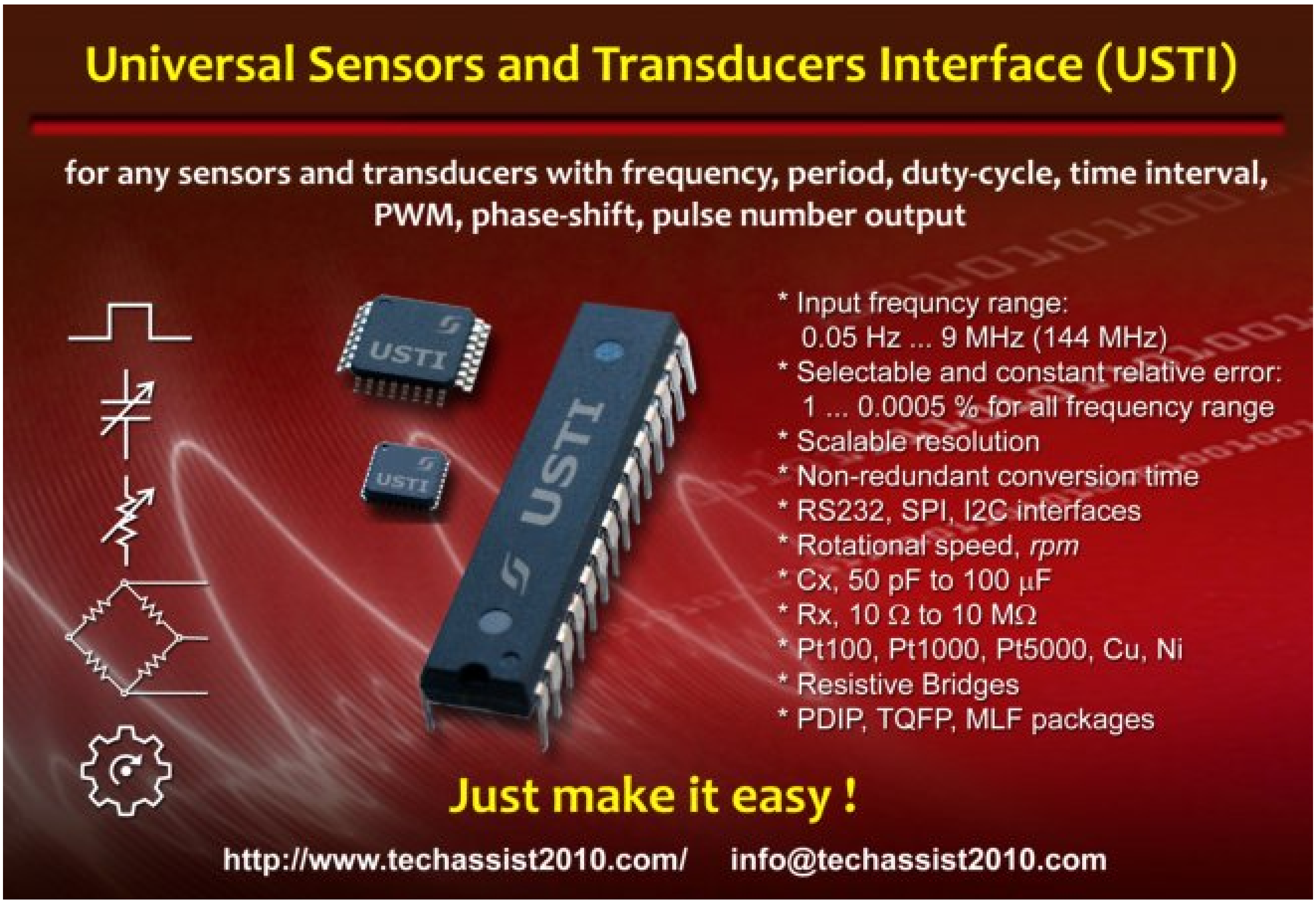
This work presented in this paper was supported by National Nature Science Foundation project China (Grant #60910005).

References

[1]. Saranli Uluc, Buehler Martin, Koditschek Daniel E., RHex: A Simple and Highly Mobile Hexapod Robot, *International Journal of Robotics Research*, Vol.20, Issue 7, 2001, pp. 616-631.
[2]. Saranli Uluc, Koditschek, Daniel E., Template based control of hexapedal running, *in Proceedings of the*

IEEE International Conference on Robotics and Automation, 14-19 September, 2003, pp. 1374-1379.
[3]. Mustafa Mert Ankarali, Control of Hexapedal Pronking Through a Dynamically Embedded Spring-Loaded Inverted Pendulum Template, PhD Thesis, *Middle East Technical University*, 2010.
[4]. Soyguder S, Alli H., Kinematic and dynamic analysis of a hexapod walking–running–bounding gait robot and control actions, *Computers and Electrical Engineering*, in press.
[5]. Saranli Uluc, Dynamic locomotion with a Hexapod Robot, PhD Thesis, *Computer Science and Engineering in The University of Michigan*, 2002.
[6]. http://www.tekscan.com/
[7]. http://www.advantech.com.cn/
[8]. S. Mallat, A wavelet tour of signal processing, *Academic Press*, 1999.

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



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 additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc. 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/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

Advertising Information

Advertising orders and enquires may be sent to sales@sensorsportal.com Please download also our media kit: http://www.sensorsportal.com/DOWNLOADS/Media_Kit_2012.pdf

IFSA

International Frequency Sensor Association Publishing

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 practicians, 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