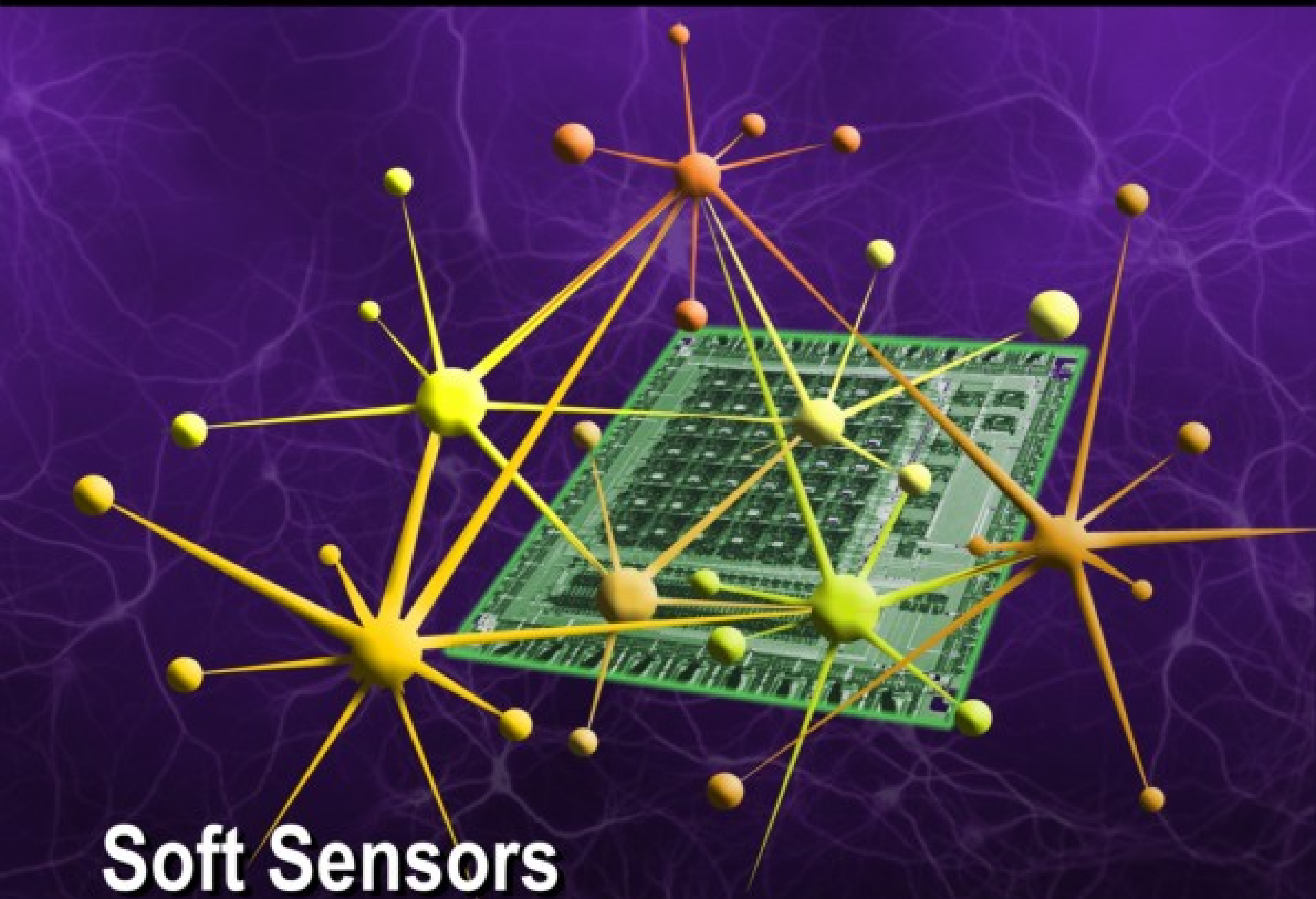
ISSN 1726-5749

SENSORS & TRANSDUCERS

10/07 vol. 84



Soft Sensors and Artificial Neural Networks

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 84
Issue 10
October 2007

www.sensorsportal.com

ISSN 1726-5479

Editor-in-Chief: professor Sergey Y. Yurish, phone: +34 696067716, fax: +34 93 4011989,
e-mail: editor@sensorsportal.com

Editors for Western Europe
Meijer, Gerard C.M., Delft University of Technology, The Netherlands
Ferrari, Vitorio, 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

Editorial Advisory Board

Abdul Rahim, Ruzairi, Universiti Teknologi, Malaysia
Ahmad, Mohd Noor, Nothern University of Engineering, Malaysia
Annamalai, Karthigeyan, National Institute of Advanced Industrial Science and Technology, Japan
Arcega, Francisco, University of Zaragoza, Spain
Arguel, Philippe, CNRS, France
Ahn, Jae-Pyoung, Korea Institute of Science and Technology, Korea
Arndt, Michael, Robert Bosch GmbH, Germany
Ascoli, Giorgio, George Mason University, USA
Atalay, Selcuk, Inonu University, Turkey
Atghiaee, Ahmad, University of Tehran, Iran
Augutis, Vygantas, Kaunas University of Technology, Lithuania
Avachit, Patil Lalchand, North Maharashtra University, India
Ayesh, Aladdin, De Montfort University, UK
Bahreyni, Behraad, University of Manitoba, Canada
Baoxian, Ye, Zhengzhou University, China
Barford, Lee, Agilent Laboratories, USA
Barlingay, Ravindra, Priyadarshini College of Engineering and Architecture, India
Basu, Sukumar, Jadavpur University, India
Beck, Stephen, University of Sheffield, UK
Ben Bouzid, Sihem, Institut National de Recherche Scientifique, Tunisia
Binnie, T. David, Napier University, UK
Bischoff, Gerlinde, Inst. Analytical Chemistry, Germany
Bodas, Dhananjay, IMTEK, Germany
Borges Carval, Nuno, Universidade de Aveiro, Portugal
Bousbia-Salah, Mounir, University of Annaba, Algeria
Bouvet, Marcel, CNRS – UPMC, France
Brudzewski, Kazimierz, Warsaw University of Technology, Poland
Cai, Chenxin, Nanjing Normal University, China
Cai, Qingyun, Hunan University, China
Campanella, Luigi, University La Sapienza, Italy
Carvalho, Vitor, Minho University, Portugal
Cecelja, Franjo, Brunel University, London, UK
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
Chen, Rongshun, National Tsing Hua University, Taiwan
Cheng, Kuo-Sheng, National Cheng Kung University, Taiwan
Chiriac, Horia, National Institute of Research and Development, Romania
Chowdhuri, Arijit, University of Delhi, India
Chung, Wen-Yaw, Chung Yuan Christian University, Taiwan
Corres, Jesus, Universidad Publica de Navarra, Spain
Cortes, Camilo A., Universidad de La Salle, 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
Kang, Moonho, Sunmoon University, Korea South
Kaniusas, Eugenijus, Vienna University of Technology, Austria
Katake, Anup, Texas A&M University, USA
Dickert, Franz L., Vienna University, Austria
Dieguez, Angel, University of Barcelona, Spain
Dimitropoulos, Panos, University of Thessaly, Greece
Ding Jian, Ning, Jiangsu 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, University of Ulm and KTB mechatronics GmbH, Germany
Erdem, Gursan K. Arzum, Ege University, Turkey
Erkmen, Aydan M., Middle East Technical University, Turkey
Estelle, Patrice, Insa Rennes, France
Estrada, Horacio, University of North Carolina, USA
Faiz, Adil, INSA Lyon, France
Fericean, Sorin, Balluff GmbH, Germany
Fernandes, Joana M., University of Porto, Portugal
Francioso, Luca, CNR-IMM Institute for Microelectronics and Microsystems, Italy
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 Ros, Juan Jose, University of Cadiz, Spain
Granel, Annette, Goteborg University, Sweden
Graff, Mason, The University of Texas at Arlington, USA
Guan, Shan, Eastman Kodak, USA
Guillet, Bruno, University of Caen, France
Guo, Zhen, New Jersey Institute of Technology, USA
Gupta, Narendra Kumar, Napier University, UK
Hadjiloucas, Sillas, The University of Reading, UK
Hashsham, Syed, Michigan State University, USA
Hernandez, Alvaro, University of Alcala, Spain
Hernandez, Wilmar, Universidad Politecnica de Madrid, Spain
Homentcovschi, Dorel, SUNY Binghamton, USA
Horstman, Tom, U.S. Automation Group, LLC, USA
Hsiai, Tzung (John), University of Southern California, USA
Huang, Jeng-Sheng, Chung Yuan Christian University, Taiwan
Huang, Star, National Tsing Hua University, Taiwan
Huang, Wei, PSG Design Center, USA
Hui, David, University of New Orleans, USA
Jaffrezic-Renault, Nicole, Ecole Centrale de Lyon, France
Jaime Calvo-Galleg, Jaime, Universidad de Salamanca, Spain
James, Daniel, Griffith University, Australia
Janting, Jakob, DELTA Danish Electronics, Denmark
Jiang, Liudi, University of Southampton, UK
Jiao, Zheng, Shanghai University, China
John, Joachim, IMEC, Belgium
Kalach, Andrew, Voronezh Institute of Ministry of Interior, Russia
Rodriguez, Angel, Universidad Politecnica de Cataluna, Spain
Rothberg, Steve, Loughborough University, UK

Kausel, Wilfried, University of Music, Vienna, Austria
Kavasoglu, Nese, Mugla University, Turkey
Ke, Cathy, Tyndall National Institute, Ireland
Khan, Asif, Aligarh Muslim University, Aligarh, India
Kim, Min Young, Koh Young Technology, Inc., Korea South
Ko, Sang Choon, Electronics and Telecommunications Research Institute, Korea South
Kockar, Hakan, Balikesir University, Turkey
Kotulska, Malgorzata, Wroclaw University of Technology, Poland
Kratz, Henrik, Uppsala University, Sweden
Kumar, Arun, University of South Florida, USA
Kumar, Subodh, National Physical Laboratory, India
Kung, Chih-Hsien, Chang-Jung Christian University, Taiwan
Lacnjevac, Caslav, University of Belgrade, Serbia
Laurent, Francis, IMEC , Belgium
Lay-Ekuakille, Aime, University of Lecce, Italy
Lee, Jang Myung, Pusan National University, Korea South
Lee, Jun Su, Amkor Technology, Inc. South Korea
Lei, Hua, National Starch and Chemical Company, USA
Li, Genxi, Nanjing University, China
Li, Hui, Shanghai Jiaotong University, China
Li, Xian-Fang, Central South University, China
Liang, Yuanchang, University of Washington, USA
Liawruangrath, Saisunee, Chiang Mai University, Thailand
Liew, Kim Meow, City University of Hong Kong, Hong Kong
Lin, Hermann, National Kaohsiung University, Taiwan
Lin, Paul, Cleveland State University, USA
Linderholm, Pontus, EPFL - Microsystems Laboratory, Switzerland
Liu, Aihua, Michigan State University, USA
Liu Changgeng, Louisiana State University, USA
Liu, Cheng-Hsien, National Tsing Hua University, Taiwan
Liu, Songqin, Southeast University, China
Lodeiro, Carlos, Universidade NOVA de Lisboa, Portugal
Lorenzo, Maria Encarnacio, Universidad Autonoma de Madrid, Spain
Lukaszewicz, Jerzy Pawel, Nicholas Copernicus University, Poland
Ma, Zhanfang, Northeast Normal University, China
Majstorovic, Vidosav, University of Belgrade, Serbia
Marquez, Alfredo, Centro de Investigacion en Materiales Avanzados, Mexico
Matay, Ladislav, Slovak Academy of Sciences, Slovakia
Mathur, Prafull, National Physical Laboratory, India
Maurya, D.K., Institute of Materials Research and Engineering, Singapore
Mekid, Samir, University of Manchester, UK
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, Benemirita Universidad Autonoma de Puebla, Mexico
Moradi, Majid, University of Kerman, Iran
Morello, Rosario, DIMET, University "Mediterranea" of Reggio Calabria, Italy
Mounir, Ben Ali, University of Sousse, Tunisia
Mukhopadhyay, Subhas, Massey University, New Zealand
Neelamegam, Periasamy, Sastra Deemed University, India
Neshkova, Milka, Bulgarian Academy of Sciences, Bulgaria
Oberhammer, Joachim, Royal Institute of Technology, Sweden
Ould Lahoucin, University of Guelma, Algeria
Pamidighanta, Sayanu, Bharat Electronics Limited (BEL), India
Pan, Jisheng, Institute of Materials Research & Engineering, Singapore
Park, Joon-Shik, Korea Electronics Technology Institute, Korea South
Pereira, Jose Miguel, Instituto Politecnico de Setebal, Portugal
Petsev, Dimiter, University of New Mexico, USA
Pogacnik, Lea, University of Ljubljana, Slovenia
Post, Michael, National Research Council, Canada
Prance, Robert, University of Sussex, UK
Prasad, Ambika, Gulbarga University, India
Prateepasen, Asa, Kingmoungut's University of Technology, Thailand
Pullini, Daniele, Centro Ricerche FIAT, Italy
Pumera, Martin, National Institute for Materials Science, Japan
Radhakrishnan, S. National Chemical Laboratory, Pune, India
Rajanna, K., Indian Institute of Science, India
Ramadan, Qasem, Institute of Microelectronics, Singapore
Rao, Basuthkar, Tata Inst. of Fundamental Research, India
Reig, Candid, University of Valencia, Spain
Restivo, Maria Teresa, University of Porto, Portugal
Rezazadeh, Ghader, Urmia University, Iran
Robert, Michel, University Henri Poincare, France
Royo, Santiago, Universitat Politecnica de Catalunya, Spain
Sadana, Ajit, University of Mississippi, USA
Sandacci, Serghei, Sensor Technology Ltd., UK
Sapozhnikova, Ksenia, D.I.Mendeleyev Institute for Metrology, Russia
Saxena, Vibha, Bhbha Atomic Research Centre, Mumbai, India
Schneider, John K., Ultra-Scan Corporation, USA
Seif, Selemani, Alabama A & M University, USA
Seifter, Achim, Los Alamos National Laboratory, USA
Sengupta, Deepak, Advance Bio-Photonics, India
Shearwood, Christopher, Nanyang Technological University, Singapore
Shin, Kyuho, Samsung Advanced Institute of Technology, Korea
Shmaliy, Yuriy, Kharkiv National University of Radio Electronics, Ukraine
Silva Girao, Pedro, Technical University of Lisbon Portugal
Slomovitz, Daniel, UTE, Uruguay
Smith, Martin, Open University, UK
Soleymanpour, Ahmad, Damghan Basic Science University, Iran
Somani, Prakash R., Centre for Materials for Electronics Technology, India
Srinivas, Talabattula, Indian Institute of Science, Bangalore, India
Srivastava, Arvind K., Northwestern University
Stefan-van Staden, Raluca-Ioana, University of Pretoria, South Africa
Sumriddetchka, Sarun, National Electronics and Computer Technology Center, Thailand
Sun, Chengliang, Polytechnic University, Hong-Kong
Sun, Dongming, Jilin University, China
Sun, Junhua, Beijing University of Aeronautics and Astronautics, China
Sun, Zhiqiang, Central South University, China
Suri, C. Raman, Institute of Microbial Technology, India
Sysoev, Victor, Saratov State Technical University, Russia
Szewczyk, Roman, Industrial Research Institute for Automation and Measurement, Poland
Tan, Ooi Kiang, Nanyang Technological University, Singapore,
Tang, Dianping, Southwest University, China
Tang, Jaw-Luen, National Chung Cheng University, Taiwan
Thumbavanam Pad, Kartik, Carnegie Mellon University, USA
Tsiantos, Vassilios, Technological Educational Institute of Kaval, Greece
Tsigara, Anna, National Hellenic Research Foundation, Greece
Twomey, Karen, University College Cork, Ireland
Valente, Antonio, University, Vila Real, - U.T.A.D., Portugal
Vaseashta, Ashok, Marshall University, USA
Vazques, Carmen, Carlos III University in Madrid, Spain
Vieira, Manuela, Instituto Superior de Engenharia de Lisboa, Portugal
Vigna, Benedetto, STMicroelectronics, Italy
Vrba, Radimir, Brno University of Technology, Czech Republic
Wandelt, Barbara, Technical University of Lodz, Poland
Wang, Jiangping, Xi'an Shiyou University, China
Wang, Kedong, Beihang University, China
Wang, Liang, Advanced Micro Devices, USA
Wang, Mi, University of Leeds, UK
Wang, Shinn-Fwu, Ching Yun University, Taiwan
Wang, Wei-Chih, University of Washington, USA
Wang, Wensheng, University of Pennsylvania, USA
Watson, Steven, Center for NanoSpace Technologies Inc., USA
Weiping, Yan, Dalian University of Technology, China
Wells, Stephen, Southern Company Services, USA
Wolkenberg, Andrzej, Institute of Electron Technology, Poland
Woods, R. Clive, Louisiana State University, USA
Wu, DerHo, National Pingtung University of Science and Technology, Taiwan
Wu, Zhaoyang, Hunan University, China
Xiu Tao, Ge, Chuzhou University, China
Xu, Tao, University of California, Irvine, USA
Yang, Dongfang, National Research Council, Canada
Yang, Wuqiang, The University of Manchester, UK
Ymeti, Aurel, University of Twente, Netherland
Yu, Haihu, Wuhan University of Technology, China
Yufera Garcia, Alberto, Seville University, Spain
Zagnoni, Michele, University of Southampton, UK
Zeni, Luigi, Second University of Naples, Italy
Zhong, Haoxiang, Henan Normal University, China
Zhang, Minglong, Shanghai University, China
Zhang, Qintao, University of California at Berkeley, USA
Zhang, Weiping, Shanghai Jiao Tong University, China
Zhang, Wenming, Shanghai Jiao Tong University, China
Zhou, Zhi-Gang, Tsinghua University, China
Zorzano, Luis, Universidad de La Rioja, Spain
Zourob, Mohammed, University of Cambridge, UK

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 CD-ROM. Copyright © 2007 by International Frequency Sensor Association. All rights reserved.

Sensors & Transducers Journal

Contents

Volume 84
Issue 10
October 2007

www.sensorsportal.com

ISSN 1726-5479

Research Articles

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

International Frequency Sensor Association (IFSA).

Sensors & Transducers Journal, Vol.84, Issue 10, October 2007, pp. 1607-1618

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

A Genetic Algorithm for Optimization in Conceptual Design Phase of Robots

[*]Amir Jafari, Mohsen Safavi, Alireza Fadaei
[*]Manufacturing Engineering Department, Azad University of Dehaghan, Isfahan, Iran
Mechanical Engineering Department, Isfahan University of Technology, Isfahan, Iran
Tel.:+98-311-391-5214, fax:+98-311-391-2826
[*]E-mail: jafamir@gmail.com

Received: 19 September 2007 /Accepted: 23 October 2007 /Published: 30 October 2007

Abstract: One of the most important criteria of the industrial robots is the dynamic performance of manipulators. There are some critical parameters which determine the dynamic performance of robot manipulators. While the correlations between these parameters are complex and highly non-linear, deciding on these parameters to optimize the dynamic performance of manipulators is a difficult and time-consuming task, especially in the early conceptual design phase. The gearbox size and the lengths of the arms are parameters that have a large impact on the performance and the cost of robots. In order to perform optimization, a mathematical programming model is developed. An objective function is defined to determine optimal gearboxes and arm lengths from an acceleration capability perspective. The arm lengths are treated as continuous variables whereas the gearboxes are selected from a list of available units. This paper presents a Genetic algorithm procedure which shows how optimization can be used in the early phases of a development process in order to evaluate the potential of a concept. This study considers a three degree of freedom robot. The mathematical model is coded in the C language and optimized using the Genetic algorithm. Comparison of the obtained results with optimum values based on Complex algorithm clearly shows the advantages of the proposed method. *Copyright © 2007 IFSA.*

Keywords: Manipulator, Optimization, Genetic Algorithm

---

1. Introduction

Many engineering problems in robot design are characterized by complexity and the presence of several conflicting design objectives. This is true for the conceptual design phase as well as the detailed design phase. In this paper the focus is on the conceptual design stage and on how rather simple mathematical models could be applied together with modern technique based on Genetic algorithm in order to support the designer. With the help of the presented technique the designer could investigate different conceptual designs and evaluate how changing requirements affect the optimal design. The optimization is carried out on a three degree of freedom (DOF) serial manipulator with an offset of the lower arm from axis one. The robot is mathematically modeled and coded in the C language program based on the proposed Genetic algorithm all and calculations are done in this package. The optimization problem is formulated as minimizing the weight of the gearboxes subjected to a set of constraints. These constraints are amongst others, a reach of 2.5 meters, a payload of 100 kg, and minimum acceleration of 0.75 G in the x-y-z directions of the base frame of the robot at predefined points. In most industrial robots the actuators consist of an electric motor and a gearbox. In this paper the motors are assumed to have a constant mass and are always able to deliver sufficient amount of torque to the gearbox. The size of the gearboxes has large impact on the overall cost of the robot and is therefore an interesting parameter at the early phases of robot design. The gearboxes are treated as discrete choices with a given mass and output torque.

In the literature there exist several methods for measuring dynamic performance of manipulators when using optimization techniques. Yoshikawa, 1985, developed the dynamic manipulability ellipsoid to measure the ease of changing the end-effector velocity in different directions for fixed kinetic energy. In later years, Graettinger and Krogh, 1989, introduced a performance measure termed *acceleration radius*. For given bounds of joint torques, the corresponding acceleration radius is defined by the minimum upper bound of the magnitude of end-effector acceleration over the whole workspace. The method presented in this paper merely measures the dynamic performance by investigating the acceleration capability in some of the points within the workspace. The idea is not to present a new method for measuring the dynamic performance of manipulators, but rather to show the usefulness of optimization for evaluation and understanding of the behaviour of different concepts in the early phases of robot design.

In the following section the creation and implementation of the dynamic model is discussed. In Section three the optimization problem is formulated and subroutines calculating inverse kinematics, torques etc used in the optimization loop and the proposed Genetic algorithm is presented as well. Finally the results are presented together with a thorough discussion on the presented method.

2. The Dynamic Model

The dynamic model is created using the Lagrangian equations of motion. Lagrange's equation is very useful in deriving equations of motion using potential and kinetic energies. Since positions and velocities are used to evaluate these energies, no acceleration is involved. Thus the kinematics part of the problem is very much simplified. Formulating the equation of motion using a set of independent generalized coordinates i.e. the joint variables leads to Lagrange's equation. With a suitable choice of coordinate systems, the equations of motion can be obtained in a simple and straightforward manner. Suppose q_1, q_2 and q_3 are generalized coordinates, the general form of Lagrange's equation may be expressed as follow:

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = Q_{i(n)} \; ; \qquad i = 1,2,3 , \tag{1}$$

where

$$L = K - U , \tag{2}$$

and where $Q_{i(n)}$ is the generalized non-conservative force, *K* and *U* are the kinetic and potential energy of the system, respectively and *L* is called Lagrange's function or Lagrangian which is defined as the difference between the kinetic (*K*) and potential energy (*U*) of a mechanical system.

The *Q* does not necessarily mean force, but the product *Q* times *q* always has the dimension of work.

If the coordinate systems to each link in the robot are placed according to the Denavit-Hartenberg method used by Spong and Vidyasagar [3], it is easy and straight forward to write the transformation and rotation matrices between the different link frames. Together with the inertia matrices for every link and the jacobian for the manipulator, it is now possible to rewrite the equation of motion as:

$$M(q)\ddot{q}+V(q,\dot{q})+G(q)=Q, \tag{3}$$

This equation is called the general form of dynamical equations. The vector *V* is called the velocity coupling vector.

There are two distinct types of velocity coupling between joints. The velocity squared terms correspond to centripetal terms, and the velocity product terms correspond to the Coriolis terms. The manipulator inertia matrix *M* is symmetric and positive definite and therefore always invertible. The offdiagonal elements of *M* represent acceleration coupling effects between joints (Lung, 1999).

The text should be typed single-spaced and justified. Use Times New Roman typeface throughout the article. Center the title (18 points, bold), author(s) name(s) (14 points, bold, surname - in upper case), affiliation(s), address(es), phone number and fax number with country and city codes, e-mail and Web page URL (12 points, regular). Leave 5 blank lines below the title, and affiliation(s).

3. The Optimization Problem

The optimization problem is formulated as to minimize the weight of the gearboxes, by choosing different discrete gearboxes, and changing the lengths of the arms continuously, subjected to a few requirements on acceleration capability, reach and payload capacity. This formulation can be interpreted as to design the cheapest possible robot that still meets the acceleration demands. The acceleration should be achieved in the x- y-and z-direction of the base frame. The base frame is a coordinate system connected to the arm which is connected to the ground, i.e. arm one in Fig 2. The constraints are formulated as penalty functions added to the objective function. The optimization problem is thus formulated according to equation 4.

$$\begin{aligned} \textbf{Min: } & f(m_1,m_2,m_3)+g_1(\tau_{avalibale},\tau_{needed})+g_2(offset,a_2,a_3) \\ & +g_3(m_1,m_2,m_3,offset,a_2,a_3) \\ \textbf{s.t } & x_i^l \le x_i \le x_i^u \;\; ; \;\; i=1,\dots,6, \end{aligned} \tag{4}$$

where, the six optimization variables, x_i, are bounded between lower and upper limits. The first three optimization variables represent the size of the gearboxes whereas the other three represent the offset and the arm lengths. *f* is the sum of the weights of the gearboxes. The g_1 is a penalty function in case if the torque needed to achieve the required acceleration exceeds the torque available. The g_2 is a penalty function in case the reach requirement is not fulfilled. The last function g_3, merely sums up the torques at all joints. This is done in order to search for arm lengths which minimize the magnitude of the torques once the lightest possible set of gearboxes is found. Each penalty function is zero when the corresponding constraint is not violated and then grows exponentially with the degree of constraint violation.

How the different parts in the objective function are derived and how the Genetic algorithm works is explained in the following chapters.

3.1. Calculation Steps

In order to be able to solve the minimizing problem a few calculations are required. The acceleration requirement is handled as an ordinary constraint by setting the acceleration in the Cartesian space to the desirable value before starting the optimization process. As an argument to the penalty function g_1, the necessary torque to achieve the required acceleration in the end-effector space (Cartesian space) needs to be calculated.

In order to do this, one needs to map the end-effector acceleration into the joint space. The relation between the velocity of the end-effector and the corresponding angular velocities of the joints can be written as

$$\dot{x} = J(q).\dot{q}\,, \tag{5}$$

where *J* is the Jacobian. The acceleration is obtained by differentiating both sides with respect to time, giving

$$\ddot{x} = J(q).\ddot{q} + \frac{dJ(q)}{dt}.q\,. \tag{6}$$

Assuming that the manipulator has zero velocity before evaluation at each predefined point in the workspace, the last term in equation (6) also turns zero. Also assuming that *J(q)* is a nonsingular and square matrix, one obtains an expression for the corresponding angular accelerations by multiplying both sides with

$$\ddot{q} = J^{-1}(q).\ddot{x}\,. \tag{7}$$

Since the Jacobian $J(q)$ is highly dependent on the lengths of the arms, equation (7) needs to be calculated for every set of arms. To calculate the required torque, one also has to map the position of the robot in Cartesian space into the joint space in order to achieve the vector q that corresponds to the Cartesian position. The vector q also has to be calculated for every new set of arm lengths. By letting the result in equation (7) together with the vector q corresponding to the current position entering equation (3), the necessary torqueses Q are obtained. The other argument entering the penalty function g_1, is the available amount of torque corresponding to the current choice of mass of the gearboxes, see Table 2.

The penalty function g_2 has the lengths of the arms as arguments and the function merely sums the lengths and gives a penalty in case the sum is smaller than the required reach. The last penalty function g_3, calculates the current torque at every joint in order to make the optimization algorithm search for arm lengths which minimize the required torque once the lightest set of gearboxes is found.

3.2. The Genetic Algorithm

The contribution of current research is to solve this optimization problem using Genetic algorithm. While variables corresponded to gearbox are discrete and those corresponded to arms length are continuous, applying Genetic algorithm seems to be more promising rather than other optimal or heuristic algorithms.

Genetic Algorithm (GA) is a stochastic search technique for approximating optimal solutions within complex search spaces (Goldberg, 1989; Holland, 1975). The technique is based upon an analogy with biological evolution, in which the fitness of individual determines its ability to survive and reproduce. The GA mechanism starts by encoding the problem to produce a list of genes.

The genes are represented by numeric or alphanumeric characters. The genes are then randomly combined to produce a population of chromosomes, each of which represents a possible solution. Genetic operations (Motivation and crossover) are performed on chromosomes that are randomly selected from the population. This produces offspring.

The fitness of these chromosomes is then measured based on objective function of the model and the probability of their survival is determined by their fitness.

In the field of application of Genetic algorithms in robotics, the interested readers may referred to Barai and Nonami, 2007; Vadakkepat et al, 2007; Beldek and Leblebiciglu, 2007; Cakar et al, 2007; Velagic et al, 2006; Ghorbani et al, 2007; Mucientes et al, 2006; Barfoot et al, 2006; Mitisi et al, 2007.

3.2.1. Method of Representation

Before a genetic algorithm can be put to work on any problem, a method is needed to encode potential solutions to that problem in a form that a computer can process. To encode the solutions, consider each solution as a D-dimensional parameters vector (D is the number of variables in the model, in this typical problem, D=6). The first three parameters are discrete parameters which are corresponding with gearbox's mass (m_1, m_2, m_3), respectively. Each of them can take a value between 1 and 8 according to the Table 2. Other three parameters are continuous parameters which are corresponding to offset, the length of first arm and the length of second arm, respectively. Each parameter taking value from within user-defined bounds, as mentioned before:

$$x_i^l \le x_i \le x_i^u \quad ; \quad i = 1,...,6 . \tag{8}$$

3.2.2. Initial Population

Initially, N real-valued D-dimensional vectors are randomly generated. Each of them is considered as a chromosome. N is the size of population. The size of the population does not change during the generation process, and is one of the algorithm's control parameters. Initially, the population is randomly created and may cover the entire parameter space with uniform probability. According to Storn and Price (1997) the size of population must take values between [5D, 10D], but must be at least 4 to ensure that GA will have enough mutually different vectors to work with.

3.2.3. Method of selection

There are many different techniques which a genetic algorithm can use to select the individuals to be copied over into the next generation. In the proposed Genetic algorithm, *Roulette-wheel selection* is used as selection method. The *Roulette-wheel* is a form of fitness-proportionate selection in which the chance of a chromosome being selected is proportional to the amount by which its fitness is greater or less than its competitors' fitness. (Conceptually, this can be represented as a game of roulette - each individual gets a slice of the wheel, but more fit ones get larger slices than less fit ones. The wheel is then spun, and whichever individual "owns" the section on which it lands each time is chosen.). While each chromosome is a feasible solution, the fitness of each chromosome is measured as inverse of its corresponded objective function value.

3.2.4. Method of change

Once selection has chosen fit chromosomes, they must be randomly altered in hopes of improving their fitness for the next generation. There are two basic strategies to accomplish this. The first and simplest is called *mutation*. Just as mutation in living things changes one gene to another, so mutation in a genetic algorithm causes small alterations at single points in an individual's code. As mentioned before, each chromosome is a 6-dimensional vector, divided to two separated 3-dimensional sub-vectors. For each sub-vector, a *mutation* method is applied differs from other one applied to the next sub-vector.

The *mutation* method for first sub-vector, i.e. the one corresponded to gearbox masses, is invoked when a randomly selected number (between 0 and 1) is less than 0.5, otherwise the second *mutation* method, i.e. the one corresponded to length of offset and arms, is used. Therefore, at each stage only one of these *mutation* methods is applied.

In the first *mutation* method, one of the first sub-vector's parameter is changed to next feasible value which differs from existing value of that parameter. Since the value of parameter is corresponded to a type of selected gearbox, this *mutation* method chooses another gearbox type for the robot while other parameters are fixed.

The second *mutation* method chooses a parameter of the second sub-vector, randomly. Then assign a value between the pre-specified lower and upper bound of the corresponded variable to that parameter. The new obtained value must be different from former to prevent generating same chromosomes.

The second method is called *crossover*, and entails choosing two chromosomes to swap segments of their code, producing artificial "offspring" that are combinations of their parents. This process is intended to simulate the analogous process of recombination that occurs to chromosomes during sexual reproduction. Based on *Roulette-wheel selection*, two chromosomes are considered as parents and then the *crossover* swaps each sub-vector of each chromosome with same sub-vector of the next to regenerate two new offsprings.

3.2.5. Termination Criterion

The termination criterion determines when the GA will stop. In other words, the operations of selection, *crossover* and *mutation* are repeated until a termination condition is met. In this method, the process is terminated after 1000 generations are performed. Tests showed that 1000 generations were sufficient for convergence.

3.3. Application

In this section the proposed Genetic algorithm is applied to a three DOF manipulator with revolute joints and an offset of the lower arm from axis one. The manipulator and data are completely same to Pettersson *et. al.* 2004. A schematic diagram of the robot is shown in Fig 1.The arms are modeled as rigid bodies with a density per length unit and extension in one direction i.e. the directions describing the cross section of the arms are neglected. The geometry of the cross section has large impact on the inertia of arm one, but less influence on the inertia of the lower and upper arm. The gearboxes are modeled as point masses located at every joint and the payload is modeled as a point mass located at the end of the upper arm. The densities of the arms are considered constant. The values for each arm are shown in Table 1.

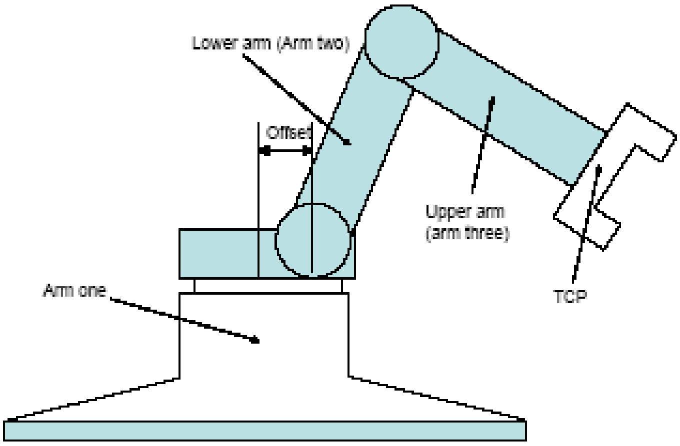


Fig. 1. Schematic diagram of the manipulator.

Table 1. Density for the different arms of the robot.

Robot arm	Density [kg/m]
Base link	1500
Offset	400
Lower arm	100
Upper arm	75

The available gearboxes for the application are shown in the list given in Table 2. All gearboxes are from the same manufacture and of the same type. Thus in order to increase the output torque, a larger gearbox is needed and hence mass increases. If gearboxes are chosen from different manufactures an alternative scenario is possible.

Then it is possible with decreasing mass with increased torque limit due to a different technology and thereby higher cost.

Furthermore, the robot should have a payload capacity of 100 kg and a minimum reach of 2.5 meters. The acceleration requirement is set to 0.75G at the predefined points in the workspace defined in Fig 2.

The performance of the robot is evaluated in x, y, and z direction at all points shown in Fig. 2 for every set of values of the design variables, i.e., gearbox size and arm length. The arms are allowed to vary within the intervals shown in Table 3.

Table 2. Torque-mass relation for available gearboxes.

Gearbox	Output torques (Nm)	Mass (kg)
1	101	2.5
2	231	4.4
3	572	9.5
4	1088	12.7
5	1499	18.0
6	2176	28.0
7	4361	47.0
8	6135	69.0

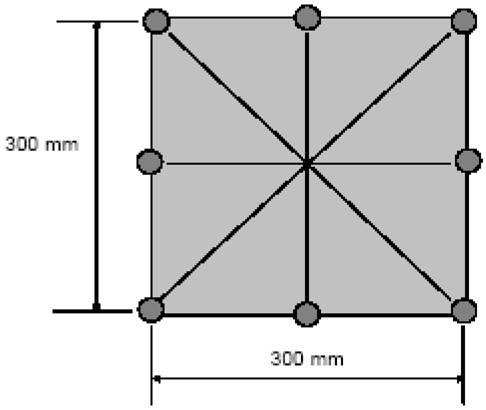


Fig. 2. Pre-defined points in workspace for performance evaluation.

Table 3. Intervals for the lengths of the arms.

Arm	Lower limit	Upper limit
Offset	0.2	0.4
Lower Arm	0.6	1.6
Upper Arm	0.6	1.4

4. Computational Results

This section discusses the performance and the computational efficiency of the proposed Genetic algorithm in comparison to the Complex algorithm proposed by Pettersson et. al. 2004. In their work, the optimization has been performed using a modified version of the Complex optimization algorithm, which is a non-gradient optimization method that extends the Nelder-Mead Simplex method for unconstraint optimization. This version of the Complex method is described in Krus and Andersson, 2003. The Complex method was first presented by Box, 1965, in the mid 60's, and is an optimal algorithm. The objective function converged into an optimum corresponding to the set of parameters shown in Table 4. The proposed Genetic algorithm was carried out several times with different initial population of chromosomes and the same optimum was found every time. The values of the design variables are too close to the result obtained by Pattersoon et. al., 2004.

As mentioned in their research, the reason that the interval of the length of offset is not increased even though the Complex and Genetic algorithms has chosen the upper boundary (offset =0.4 or =0.399) is that a larger offset would decrease the workspace volume too much. This is a constraint which is not included in the optimization and from an acceleration capability point of view it is natural to increase the offset as much as possible. Increased offset has little influence on joint one, but reduces the size of the gearboxes on axis two and three.

For comparison, Figs. 3 and 4 show how the magnitude of the mass of gearbox 1 changes during optimization based on the Complex algorithm proposed by Pettersson et. al. and on the proposed Genetic algorithm, respectively. Figs. 5 and 6 show how the length of upper arm changes during optimization of Complex and Genetic algorithms, respectively.

As it is shown in Fig. 4, in the proposed Genetic algorithm the mass of gearbox 1 is considered to be a discrete variable. As one can see in these figures, the proposed Genetic algorithm converges the solutions more quickly. This is due to the fact that Genetic algorithm is a heuristic algorithm while Complex algorithm is an optimal one. Furthermore, in Genetic algorithm, the strength point is that genetic algorithms are intrinsically parallel. Most other algorithms are serial and can only explore the solution space to a problem in one direction at a time, and if the solution they discover turns out to be sub-optimal, there is nothing to do but abandon all work previously completed and start over. However, since Genetic algorithm has multiple offsprings, it can explore the solution space in multiple directions at once.

If one path turns out to be a dead end, it can easily eliminate it and continue work on more promising avenues, giving them a greater chance each run of finding the optimal solution.

Table 4. List of optimum values of the design variables.

Design variable	Value
Gearbox number 1	47 kg, 4361 Nm
Gearbox number 2	69 kg, 6135 Nm
Gearbox number 3	12.7 kg, 1088 Nm
Length of offset	0.4 m
Length of lower arm	0.1.379 m
Length of upper arm	0.721 m

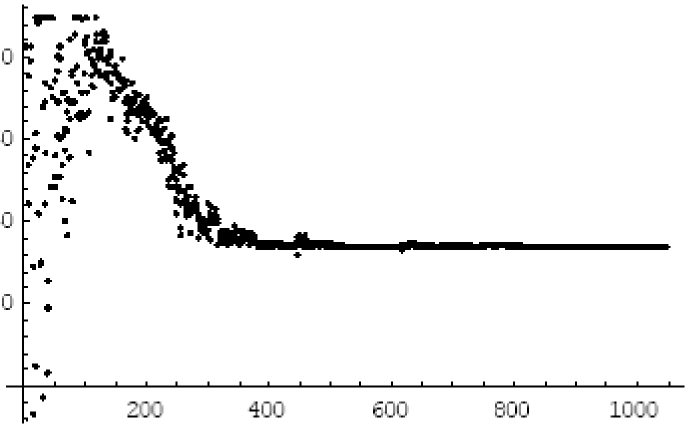


Fig. 3. The mass of gearbox 1 as function of the number of iterations(Complex algorithm).

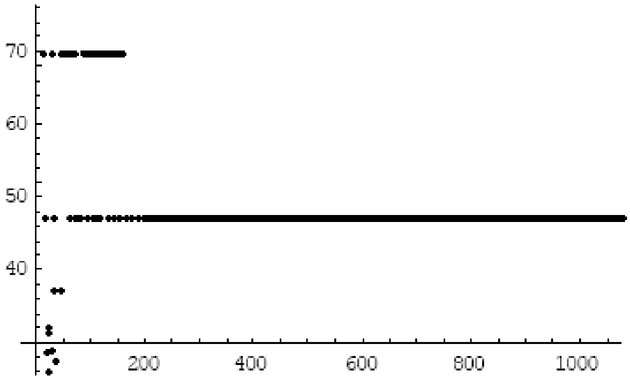


Fig. 4. The mass of gearbox 1 as function of the number of generations (proposed Genetic algorithm).

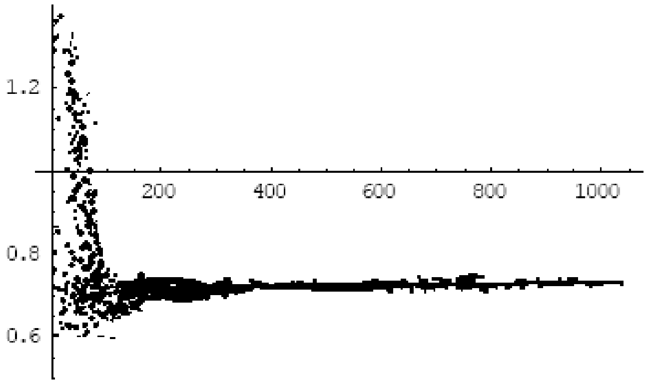


Fig. 5. The length of the upper arm as function of the number of iterations(Complex algorithm).

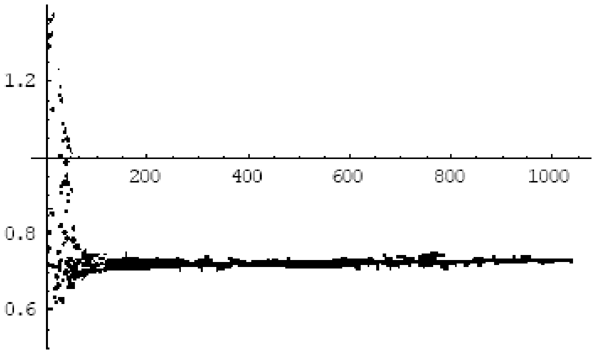


Fig. 6. The length of the upper arm as function of the number of generations (proposed genetic algorithm).

5. Conclusion and Scope for Future Works

This paper presents a method for optimization of robot design in the conceptual design stage based on Genetic algorithm. The robot is mathematically modeled and solved using Genetic algorithm through C language program. The optimization problem is formulated as to determine gearboxes and arm lengths in order to minimize the weight of the gearboxes and simultaneously obtain a prescribed acceleration at a set of points in the workspace. This formulation can be interpreted as to design the cheapest possible robot that still meets the acceleration demands. This could be time-consuming and difficult problem. The optimization method based on Genetic algorithm showed good capability in finding an optimum set of gearboxes and arm lengths for a three DOF robot manipulator. The results then compared to obtained results based on Complex algorithm proposed by Pettersson et. al., 2004, which is optimal algorithm and it was shown that the results are considerably close to the optimum values. Thus the presented method provides good support for conceptual robot design. The Complex algorithm works with continuous variables, but the gearboxes are available only as discrete alternatives. Hence, the Complex will try more alternatives than necessary.

Furthermore, it is extendable to more complex manipulators and more complicated performance measures. In this model the gearboxes had merely a maximum torque-mass relation.

A more complex model of the gearbox should contain a speed-torque dependency and inertia properties.

Furthermore the optimization would be more useful if one made the cycle based optimization and could take other characteristics such as lifetime and cycle time into account.

With the electric motor included in the optimization additional design parameters such as gear ratio would be required likewise thermal aspects must be added to the characteristics included in the objective function.

A problem when designing robots is to know for which cycles a robot design should be optimized. Cycle-based optimization is also a time-consuming task. If it was possible to translate the result from an optimization without cycle-based evaluation, like the ones presented in this paper into a more global performance index it would be of benefit for the robot designer.

References

[1]. Barai, R. K. and Nonami, K., Optimal two-degree-of-freedom fuzzy control for locomotion control of a hydraulically actuated hexapod robot, *Information Sciences*, Vol. 117, 2007, pp. 1892-1915.

[2]. Beldak, U. and Leblebiciglu, K., Strategy creation, decomposition and distribution in particle navigation, *Information Sciences*, Vol. 117, 2007, pp. 755-770.

[3]. Barfoot, T. D., Earon, E. J. P. and D’Eleuterio, G. M. T., Experiments in learning distributed control for a hexapod robot**,** *Robotics and Autonomous Systems*, Vol. 54, Issue 10, 2006, pp. 864-872.

[4]. Box, M. J., A new method of constrained optimization and a comparison with other methods, *Computer Journal*, Vol. 8, 1965, pp. 42-52.

[5]. Çakar, T., Köker, R. and Demir, H. İ., Parallel robot scheduling to minimize mean tardiness with precedence constraints using a genetic algorithm, *Advances in Engineering Software*, In Press, Corrected Proof, Available online 17 January, 2007.

[6]. Ghorbani, R., Wu, Q. and Wang, G. G., Nearly optimal neural network stabilization of bipedal standing using genetic algorithm, *Engineering Applications of Artificial Intelligence*, 2007, In Press, Corrected Proof, Available online 28 November 2006.

[7]. Graettinger, T. and Krogh B. H., The acceleration radius: A global performance measure for robotics manipulators, *J. of Robotics and Automation*, Vol. 4, No 1, 1988, pp :132-141.

[8]. Goldberg, D. E., Genetic algorithms-In research, optimization and machine learning, *Addison Wesley*, USA, 1989.

[9]. Holland, J. H., Adaptation in natural and artificial systems, The University of Michigan Press, Ann Arbor, MI, ISBN : 5215, USA, 1975.

[10].Krus, P. and Andersson J., Optimizing Optimization for Design Optimization", Proceedings of *DETC’03 2003 ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2003, Chicago, Illinois USA, pp. 21-29.

[11].Krus, P., Jansson, A. and Palmberg J. -O., Optimization for Component Selection in Hydraulic Systems, Fourth Bath International Fluid Power Workshop, *Research Studies Press Lt.,* 1991.

[12].Lung. W. T., Robot Analysis, the Mechanics of Serial and Parallel Manipulators, *John Willey & Sons Inc*, 1999, pp 395- 403.

[13].Mitsi, S., Bouzakis, K. D., Sagris, D. and Mansour, G., Determination of optimum robot base location considering discrete end-effector positions by means of hybrid genetic algorithm, *Robotics and Computer-Integrated Manufacturing*, 2007, In Press, Corrected Proof, Available online 17 October 2006.

[14].Mucientes, M., Moreno, D. L., Bugarín, A. and Barro, S., Design of a fuzzy controller in mobile robotics using genetic algorithms, *Applied Soft Computing*, 2007, In Press, Corrected Proof, Available online 20 November 2006.

[15].Pettersson, M., Krus, P., Feng, X., Andersson, J. and Wappling, D., Industrial robot design optimization in the conceptual design phase, *IEEE Mec & Rob conference*, 2004, Neworland, L. A., USA.

[16].Spong, W. M. and Vidyasagar, M., Robot Dynamics and Control, *John Willey & Sons Inc*, 1989, pp 65-71.

[17].Storn, R. and Price, K., Differential evolution-a simple and efficient heuristic for global optimization over continues spaces, *Journal Global Optimization*, Vol. 11, 1997, pp :241-354.

[18].Vadakkepat, P., Peng, X., Quek, B. K. and Lee, T. H., Evolution of fuzzy behaviors for multi-robotic system**,** *Robotics and Autonomous Systems*, Vol. 55, Issue 2, 2007, pp. 146-161.

[19].Velagic, J., Lacevic, B. and Perunicic, B., A 3-level autonomous mobile robot navigation system designed by using reasoning/search approaches, *Robotics and Autonomous Systems*, Vol. 54, Issue 12, 2006, pp. 989-1004.

[20].Yoshikawa, T. Dynamic manipulability of articulated robot arms, In *15th International Symposium on Industrial Robots*, Sept 1985.

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726- 5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

Topics Covered

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

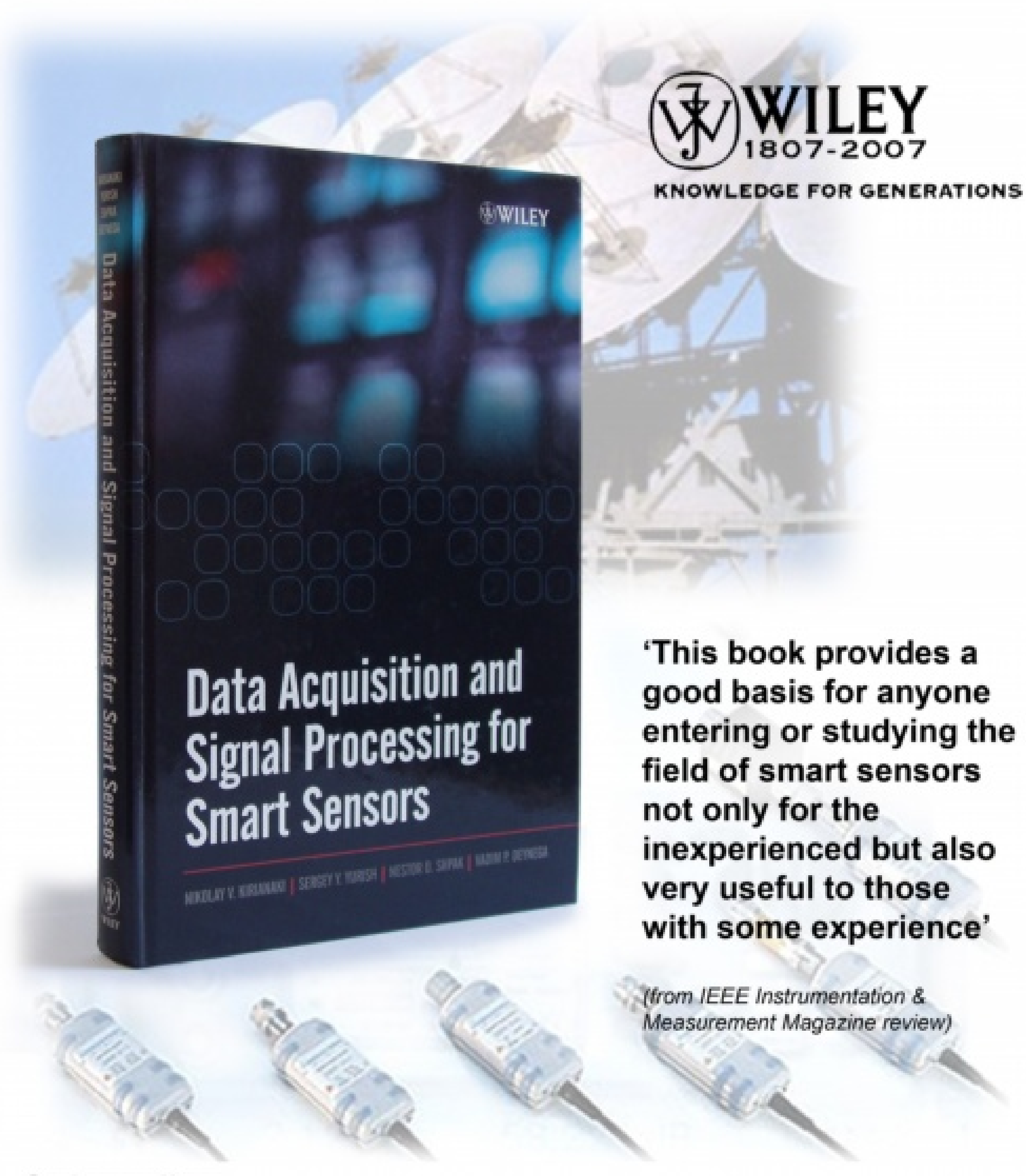
- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors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

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 6-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/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_2007.PDF


WILEY
Data Acquisition and Signal Processing for Smart Sensors
NIKOLAY V. KIRIANAKI | SERGEY Y. YURISH | NESTOR O. SHPAK | VADIM P. DEYNEGA
WILEY