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Editor-in-Chief
Prof. Janusz Kacprzyk
Systems Research Institute
Polish Academy of Sciences
ul. Newelska 6
01-447 Warsaw
Poland
E-mail: kacprzyk@ibspan.waw.pl

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Mircea Gh. Negoita
Sorin Hintea

Bio-Inspired Technologies for the Hardware of Adaptive Systems

Real-World Implementations and Applications

Springer

Prof. Mircea Gh. Negoita
24 Fiona Grove
Karori
Wellington 6012
New Zealand
E-mail: mnegoita@hotmail.com

Prof. Dr. ing. Sorin Hintea
Technical University of Cluj-Napoca
Faculty of Electronics
Telecommunications and IT Basis of Electronics Department
str G. Baritiu nr 26-28
Cluj-Napoca 400027
Romania
E-mail: Sorin.Hintea@bel.utcluj.ro

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To my country Australia – a world leader and promoter of high technology

To my native country Romania– an EU member of the world elite in high technology

Mircea Negoita

Foreword

Bio-Inspired Computing Technologies led to the spectacular progress of the Computational Intelligence (CI) nowadays and to its implementations in form of the Hybrid Intelligent Systems (HIS). Evolvable Hardware (EHW) has emerged as a novel and highly diversified technology and paradigm supporting the design, analysis and deployment of the high performance intelligent systems. The intellectual landscape of EHW is enormously rich. The discipline of EHW brings together hardware implementation of the main technologies of CI including fuzzy sets, neural networks, and evolutionary optimisation. But EHW systems use more than just the three broad areas mentioned above. They also cover novel areas as Artificial Immune Systems and DNA computing. The strength of EHW hinges on the synergy between these technologies supported by the advanced analogue and digital programmable circuits. This synergy helps exploit the advantages of the contributing technologies while reducing their possible limitations. The advanced programmable circuits confer the suitable hardware environment for a CI implementation from day to day more close to the intelligence of a human being.

EHW is a special case of the adaptive hardware, namely being strongly related to the Adaptive Systems (AS) and the Adaptive Hardware (AH).The progress in EHW is rapid. The individual technologies evolve quite quickly paving a way to new interesting and truly amazing applications. In the heart of all of those is the principle of hybridisation. EHW is suitable for the dramatic changes that happen in the relation between hardware and the application environment .This is in the case of malicious fault/ defects and need for new emergent functions that claim for in-situ synthesis of a totally new hardware configuration. It is not surprising at all witnessing a lot of activities and achievements within this realm included on the agenda of high tech organizations as NASA or ESA.

It is my pleasure indeed to introduce an attempt to provide the basis for EHW /AH through a comprehensive presentation of the fundamentals, key methods and the recent trends. The authors are two well-known researchers – both of them having a large industrial and academic experience: Professor Mircea Gh. Negoita of BLA Ltd, Brisbane, Australia and Professor Sorin Hintea of The Technical University of Cluj-Napoca, Romania. Both of them have a successful track record in this area and are highly qualified for this job. Consequently, the book has immensely benefited from their individual research, professional insights and practical experience.

I am convinced that the book will be a useful tool in pursuing further developments and applications of EHW/AH methods and circuits. The editors are to be congratulated on the careful selection of the material that very well reflects the breadth of the discipline covering a range of highly relevant and practical design principles governing the development of EHW/AH. Given this amazingly wide scope of the area, the reader will be pleased by the depth and clarity of exposure of the material. A newcomer will be pleased by the comprehensive and well-organized material of the volume. A practitioner will gain a down-to-the earth view at the design principles useful in the design, implementation, and validation of EHW/AH that rely on intelligent systems. This volume supplements very well the previous book by Negoita et al. entitled "Computational Intelligence. Engineering of Hybrid Systems" being already published in 2004 and the co-edited book by Negoita and Reusch entitled "Real World Applications of Computational Intelligence" already published in 2005.

The authors deserve our congratulations on their outstanding work. The authoritative coverage of the area is performed through a clear and well-organised way of presenting the fundamentals of key methods. This feature makes the book highly attractive. It is an excellent reading for everybody who is practically interested in the design and analysis of EHW/AH.

Charles C Nguyen, D.Sc.
Dean and Professor
Nguyen@cua.edu
October 15, 2008

School of Engineering
Catholic University of America
Washington DC, USA

Preface

Problems in engineering, computational science and the physical and biological sciences are using the increasingly sophisticated methods of Computational Intelligence (CI). This science/engineering field is mainly the result of an increasing merger of the stand alone Intelligent Technologies (IT), namely Fuzzy Systems (FS), Neural Networks (NN) , Evolutionary Computation (EC) , Artificial Immune Systems (AIS), DNA Computing and Knowledge Based Expert Systems (KBES). Because of the high interdisciplinary requirements featuring most real-world applications, no bridge exists between the different stand alone ITs. These technologies are providing *increasing benefit to business and industry*. The concomitant increase in dialogue and interconnection between the ITs has led to CI and its practical engineering implementation – the Hybrid Intelligent Systems (HIS).

Hardware implementation synergy of the main CI technologies including fuzzy sets, neural networks, and evolutionary optimization led to Evolvable Hardware (EHW). This is a novel and high performance technology and paradigm supporting the design, analysis and deployment of the high performance intelligent systems. EHW is a technical component typically featuring the most advanced structures of the Adaptive Systems (AS) and the most flexible Adaptive Hardware (AH). Nevertheless, it is hardware implementation of the most benefit for the society and indeed most revolutionizing application of CI by leading to the so-called EHW. These new CI based methodologies make possible the hardware implementation of both genetic encoding and artificial evolution, having a new brand of machines as a result. This type of machines is evolved to attain a desired behaviour that means they have a *behavioural computational intelligence*. There is no more difference between adaptation and design concerning these machines, these two concepts representing no longer opposite concepts. A dream of technology far years ago currently became reality: adaptation transfer from software to hardware is possible by the end. Much more, the electronics engineering as a profession was radically changed: the most soldering-based assembling manufacturing technologies are largely replaced now by technologies that use the strong technological support of advanced VLSI programmable circuitry, including EHW technologies. EHW can overcome a lot of technological manufacturing problems of the electronics integrated circuits: fabrication mismatches, drifts, temperature and other plagues to analog, exploiting the actual on-chip resources – finding a new circuit solution to the requirements with given constrains and actual on-chip resources.

EHW design methodology for the electronic circuits and systems is not a fashion. It is suitable for solving the special uncertain, imprecise or incomplete defined real-world problems, claiming a continuous adaptation and evolution too. Dramatic changes happen in the relation between hardware and the application environment, and this in case of *malicious faults* or need for *emergent new functions* that claim for in-situ synthesis of a totally new hardware configuration. EHW is suitable for flexibility and survivability of autonomous intelligent systems. EHW *survivability* means to maintain functionality coping with changes in hardware characteristics under the circumstances of adverse environmental conditions as for example: temperature variations, radiation impacts, aging and malfunctions. EHW *flexibility* means the availability to create new functionality required by changes in requirements or environment. The application developer may meet different design tasks to be evolved. As the case, the design to be evolved could be: a program, a model of hardware or the hardware itself. Algorithms that run outside the reconfigurable hardware, mainly feature the actual EHW state of the art. But also some chip level attempts were done. The path from chromosome to behaviour data-file is different in case of intrinsic and extrinsic EHW.

The progress in EHW is rapid. The expanding of EHW area of application nowadays is similar to Fuzzy technology in the last twenty years. Beginning with space and defense applications a few years ago, EHW/AHS is applied in humanoid robots for intelligent handling, EMG-prosthetic hand, and data compression for graphic arts, cellular phones, polymorphic electronics, self-repairing hardware and so on. It is not surprising at all witnessing the growing up of the EHW/AHS community as a distinct elite group inside the international scientific community of CI. The main EHW/AHS international conferences, workshops, symposia are supported by famous international research organizations, as NASA from USA or ESA from EU. Some reference research groups marked the previous and current trends and achievements of the EHW/AHS community at a world level: NASA JPL Evolvable Hardware Laboratory, USA; EHW Group at the Advanced Semiconductor Research Center of National Institute of Advanced Industrial Science and Technology (AIST), Japan; EHW Group at the Intelligent Systems Research Group of the University of York, UK; EHW Group at Department of Computer Systems, The Faculty of Information Technology (FIT), Brno University of Technology, Czech Republic; The Reconfigurable and Embedded Digital Systems Institute (REDS) at The University of Applied Sciences (HEIG-VD), Switzerland.

The idea of writing a book on this topic first crossed my mind in 2001, and I am really happy that the book is finally complete. Initially I thought this book would be of real help to my gifted students at the School of IT at Wellington Institute of Technology, Wellington, New Zealand. New ideas and suggestions crucially guiding the final structure of the book were used as a result of my research visit at NASA JPL in 2003 and as a result of my direct contacts and involvement in organizing the NASA/DoD EHW series of conferences.

The purpose of this book is to illustrate the current needs and to emphasize the future needs for the interaction between various component parts of the EHW/AHS framework. The team writing this book did this firstly by encouraging the ways that EHW techniques may be applied in those areas where they are already

traditional, as well as pointing towards new and innovative areas of application involving emergent technologies such as Artificial Immune Systems. Secondly, the team aimed to help encourage other disciplines to engage in a dialogue with practitioners of EHW/AHS engineering, outlining their problems in accessing these new methods in the engineering of intelligent AS, and also suggesting innovative developments within the area itself. Thus the progress of EHW/AH within the framework of intelligent AS was discussed from an application - engineering point of view, rather than from a cognitive science or philosophic view point. In this respect, regarding the technological support of EHW/AH the team of authors is most focused on the analog reconfigurable hardware that has actually a huge weight in the EHW environment. The appearance of reconfigurable analogue arrays (FPAAs) was crucial for the technological support required by companies involved in electronics research and development as well as in manufacturing. The analog reconfigurable hardware allows prevention or removal of essential fabrication mismatches and other refined technological problems by evolving circuits as the case. Practical engineering comments are made regarding the so-called *custom made* EHW-*oriented reconfigurable hardware* that can reprogram many times, can understand what's inside and is featured by a flexible programmability.

Beside some concrete elements of the EHW design, the book delivers a global image of the current limits in evolutionary design of AH. Also the practitioners get an accurate image of two different and distinct approaches governing EHW/AH: *Evolutionary circuit design* performs the evolution (the design) of a single circuit, with additional features such as fault tolerance, testability, polymorphic behaviour, that are difficult to design by conventional methods; *Evolvable hardware* involves an evolution responsible for continual adaptation applied to high-performance and adaptive systems in which the problem specification is unknown beforehand and can vary in time

Due to the best efforts of both co-authors, the book looks like a homogenous work aimed to be accessed very comfortable to a large range of public.

Chapter 1 is an introduction to Computational Intelligence and Intelligent Hybrid Systems, focused on their terminology and classification connections to EHW/AH. Emergent Intelligent Technologies implication on the Adaptive Hardware Systems is presented. A special part describes the AIS as a special technology for the Adaptive Systems.

Chapter 2 presents an engineering perspective of the EHW terminology, design methods and application relied on very practical engineering remarks. Direct application related aspects of immediate help for any EHW practitioners are another topic of this chapter. Some EHW specific programmable integrated circuits are introduced, especially the new generation – field programmable gate arrays (FPGAs) and most recently reconfigurable analogue arrays (FPAAs) and field-programmable interconnection circuits (FPICs) or configurable digital chips at the functional block level, (open-architecture FPGAs).

Chapter 3 presents a number of Genetic Algorithms applications in the field of electronic circuits design, both analog and digital. Examples of logic circuits are introduced, including arithmetic circuits designed using evolutionary techniques, and the results are compared with the conventional methods. Another promising

field of application is consisting of reconfigurable circuits applied in mobile communications, as a part of more complex adaptive systems. Also, there are proposed biomedical applications such as the implanted auditory prosthesis and other electronic stimulators. It is included a description of an AO design method based on fuzzy techniques and genetic algorithms.

Most sub-chapters include useful suggestions for the practical design and development of further applications. Both authors agree that although this book is a primer, it is not useful to only students. This book has practical value for both those new to the discipline and also for those who are already practitioners in the area.

The common research work and exchange of ideas with my distinguished colleague – constitutes the foundation for this book. Professor Sorin Hintea, from the Technical University of Cluj-Napoca, from my native country - Romania is a world known personality acting inside a very promising EHW/AH high tech European research group.

A decisive element for finally completing the book was the support of EHW/AH Group at NASA JPL, the special remarks and advice from its leader - dr. Adrian Stoica. Special thanks are due to Prof. Lukas Sekanina , Faculty of Information Technology, Brno University of Technology, for our permanent interactive scientific connection.

The authors are grateful for the understanding and permanent support of Springer Verlag Publishing House throughout the writing of this book. We would also like to acknowledge our special appreciation for the permanent support of dr. Robert J. Howlett - the Executive Chairman of KES International Organization - a leading professional organization that strongly supports and promotes EHW/AH technologies, conferences and publications.

On behalf of both authors,

Queensland, Australia
October 15, 2008

Bongaree, Bribie Island
Prof. Mircea Gh. Negoita

Contents

List of Acronymes

A	**A***denine* (*a* **DNA** *base*)
ABR	**A***rchitecture* **B***it* **R***egisters*
ADC	**A***nalogue – to -* **D***igital* **C***onverter*
AEH	**A***daptive and* **E***volvable* **H***ardware*
AGC	**A***utomatic* **G***ain* **C***ontrol*
AH	**A***daptive* **H***ardware*
AI	**A***rtificial* **I***ntelligence*
AIS	**A***daptive* **I***mmune* **S***ystem*
AIS	**A***rtificial* **I***mmune* **S***ystem*
AMR	**A***dvanced* **RISC** **M***achine*,
ANFIS	**A***daptive* **N***euro -* **F***uzzy* **I***nference* **S***ystem*
APC	**A***ntigen-***P***resenting* **C***ells*
AS	**A***daptive* **S***ystem*
ASIC	**A***pplication-***S***pecific* **I***ntegrated* **C***ircuit*
B-cells	**B***-lymphocytes*
BCA	**B-c***ell* **A***lgorithm*
BDD	**B***inary* **D***ecision* **D***iagram*
BDT	**B***inary* **D***ecision* **T***ree*
BioMEMS	**Bio***medical* **MEMS**
BIST	**B***uilt – I**n – S**elf – T**est*
BPF	**B***and* **P***ass* **F***ilter*
C	**C***ytosine*
CA	**C***ellular* **A***utomata*
CAP	**C***onfigurable* **A***nalog* **P***rocessor*
CDN	**C***urrent* **D***ivision* **N***etwork*
CI	**C***omputational* **I***ntelligence*
CPLD	**C***omplex* **P***rogrammable* **L***ogic* **D***evices*

CPU	**C***entral* **P***rocessing* **U***nit*
CWP	**C***omputing with* **W***ord and* **P***erception*
DAC	**D***igital – to -* **A***nalogue* **C***onverter*
DCR	**D***irect –* **C***onversion* **R***eceiver*
DGA	**D***esigner* **G***enetic* **A***lgorithms*
DN	**D***istribution* **N***etwork*
DNA	**D***eoxyribo* **N***ucleic* **A***cid*
DNA-AIS	**H***ybridization between* **DNA** *systems and* **AIS**
DNA-FS	**H***ybridization between* **DNA** *systems and* **FS**
DNA-NN	**H***ybridization between* **DNA** *systems and* **NN**
DNA-GA	**H***ybridization between* **DNA** *systems and* **GA**
DSP/ASIC	**D***igital* **S***ignal* **P***rocessor/* **ASIC** *(a hybrid solution onto a configurable core featured by the best of both* **DSP** *and* **ASIC** *architectures)*
EA	**E***volutionary* **A***lgorithms*
EC	**E***volutionary* **C***omputation*
EC -AIS	**H***ybridization between* **EC** *systems and* **AIS**
EHW	**E***volvable* **H***ard***W***are*
EHW-AIS	**H***ybridization between* **EHW** *systems and* **AIS**
ES	**E***volutionary* **S***trategy*
EP	**E***volutionary* **P***latform*
EUNITE	**E***uropean* **N***etwork on* **I***ntelligent* **T***echnologies for*
EW	**E***lectronic* **W***arfare*
FES	**F***unctional* **E***lectrical* **S***timulation*
FNS	**F***unctional* **N***euromuscular* **S***timulation*
FPAA	**F***ield* **P***rogrammable* **A***nalog* **A***rrays*
FPGA	**F***ield* **P***rogrammable* **G***ate* **A***rrays*
FPIC	**F***ield* **P***rogrammable* **I***nterconnection* **C***ircuits*
FL	**F***uzzy* **L***ogic*
FPMA	**F***ield* **P***rogrammable* **M***ixed-signal* **A***rray*
FPTA	**F***ield* **P***rogrammable* **T***ransistor* **A***rrays*
FPPA	**F***ield* **P***rogrammable* **P***rocessor* **A***rrays*
FS	**F***uzzy* **S***ystem*
FS-AIS	**H***ybridization between* **AIS** *systems and* **FS**
FSM	**F***inite* **S***tate* **M***achines*
G	**G***uanine*
GA	**G***enetic* **A***lgorithm*

GA-FS	**H***ybridization between* **GA** *systems and* **FS**
GA-NN	**H***ybridization between* **GA** *systems and* **NN**
GA-NN-FS	**H***ybridization between* **GA** *systems,* **NN** *systems and* **FS** *systems*
GAP	**G***enetic* **A***lgorithm* **P***rocessor*
GP	**G***enetic* **P***rogramming*
HIS	**H***ybrid* **I***ntelligent* **S***ystems*
HOT	**H***ardware* **O***bject* **T***echnology*
HPRCs	**H***igh* **P***erformanc*e **R***econfigurable* **C***omputers*
HPF	**H***igh* **P***ass* **F***ilter*
I/O	**I**nput**/O***utput interface*
IIM	**I***nnate* **I***mmune* **S***ystem*
IT	**I***ntelligent* **T***echnologies*
ITS	**I***ntelligent* **T***utoring* **S***ystems*
IT-2 FP	**I***nterva*l **T***ype-***2** **F***uzzy* **P***rocessors*
IT2-FLS	**I***nterva*l **T***ype-***2** **F***uzzy* **L***ogic* **S***ystem*
JPL	(**NASA**) **J***et* **P***ropulsion* **L***aboratory*
KBES	**K***nowledge* **B***ased* **E***xpert* **S***ystems*
KDD	**K***nowledge* **D***iscovery in* **D***ata Bases*
LNA	**L***ow - Noise* **A***mplifier*
LPF	**L***ow* **P***ass* **F***ilter*
MC	**M***olecular* **C***omputing*
MEMS	**M***icro-***E***lectro-***M***echanical* **S***ystems*
MPU	**M***ain* **P***rocessing* **U***nit*
MLCEA-TC	**M***ulti-***L***ayer* **C***hromosome* **E***volutionary* **A***lgorithm –* **T***ransistor* **C***ount*
NESW	**N***orth- East-South-West interconnection*
NGA	**N***agoya* **GA**
NN	**N***eural* **N***etworks*
NW-AIS	**n***etwork-***b***ased* **AIS**
OTA	**O***perational* **T***rans-conductance* **A***mplifiers*
PAL	**P***rogrammable* **A***rray* **L***ogic*
PAMA	**P***rogrammable* **A***nalog* **M***ultiplexer* **A***rray*
PB-AIS	**p***opulation-***b***ased* **AIS**
PCR	**P***olymerase* **C**hain **R***eaction*
PCI	**P***eripheral* **C***omponent* **I***nterconnect* Standard
PDC	**P***ersonal* **D***igital* **C***ellphone*

PFU	**P***rogrammable* **F***loating* **U***nit*
PGA	**P***rogrammable* **G***ain* **A***mplifier*
PLA	**P***rogrammable* **L***ogic* **A***rray*
PLD	**P***rogrammable* **L***ogic* **D***evices*
PTA	**P***rogrammable* **T***ransistor* **A***rray*
PROM	**P***rogrammable* **R***ead-***O***nly* **M***emory*
PSO	**P***article* **s***warm* **o***ptimization*
PSO-DR	**P***article* **s***warm* **o***ptimization with* **d***iscrete* **r***ecombination*
PSoC	**P***rogrammable* **S***ystem-***o***n-***C***hip*
QC	**Q***uantum* **C***omputing*
RAT	**R***adio* **A***ccess* **T***echnologies*
RH	**R***econfigurable* **H***ardware*
RHIS	**R***obust* (**S***oft* **C***omputing*) **I***ntelligent* **S***ystems*
RISC	**R***educed* **I***nstruction* **S***et* **C***omputer architecture*
RLC	**R***einforcement* **L***earning* **C***omponent*
RLD	**R***econfigurable* **L***ogic* **D***evice*
RM	**R***econfigurable* **M***echanism* (**RM**)
RNA	**R***ibo* **N***ucleic* **A***cid*
RPU	**R***econfigurable* **P***rocessing* **U***nit*
SABLES	**S***tand-***A***lone* **B***oard-***L***evel* **E***volvable* **S***ystem*
SAS	**S***mart* **A***daptive* **S***ystem*
SC	**S***oft* **C***omputing*
SDR	**S***oftware* **D***efined* **R***adio*
SGA	**S***imple* **GA** (*A classical Goldberg's* **GA**)
SME	**S***mall and* **M***edium* **E***nterprises*
SoPC	**S***ystems* **o***n* **P***rogrammable* **C***hip*
SRAM	**S***tatic* **R***andom* **A***ccess* **M***emory*
SS	**S***mart* **S***ystem*
S-W	**S***mith-***W***aterman* algorithm
T-cells	**T***-lymphocytes (T-cells*
T	**T***hymine*
TI DSP	**T***exas* **I***nstrument***s** **DSP**
T2-FLS	**T***ype-***2** **F***uzzy* **L***ogic* **S***ystem*
TRAC	**T***otally* **R***ecofigurable* **A***nalog* **C***ircuit*
UMTS	**U***niversal* **M***obile* **T***elecommunications* **S***ystem*
VGA	**V***ariable* **G***ain* **A***mplifier*

VHDL	**V***ery* **H***igh-speed integrated Circuit* **H***ardware* **D***escription* **L***anguage*
VLGGA	**V***ariable* **L***ength* **G***enotype* **G***enetic* **A***lgorithm*
VLSI	**V***ery* **L***arge* **S***cale* **I***ntegration*
VPU	**V***ector* **P***rocessing* **U***nit*
WITNeSS	**W***ellington* **I***nstitute of* **T***echnology* **N***ovel* **E***xpert* **S***tudent* **S***upport*