Fault-tolerance Methodologies
Development in Embryonic Systems with FPGA-based Hardware

Cs. SZASZ and V. CHINDRIŞ

Abstract: The paper deals with the multi-cellular artificial organisms’ computer-aided modeling, numerical simulation and experimental research, in order to design and implement digital systems with abilities of biological organisms, such as: evolution capabilities, self-healing, and fault-tolerance. It is proposed and developed a new model for an FPGA-based artificial cell, and the complex interaction phenomena between a bi-dimensional structure cell networks is analyzed and simulated. The fault-tolerance properties through specially developed algorithms were implemented. The final purpose is to design and experiment a bio-inspired hardware system (embryonic machine) with programmable FPGA arrays, for study and experiment basic properties of living organisms.

Keywords: FPGA circuit, bio-inspired hardware, artificial cell, fault-tolerance, self-healing

1. INTRODUCTION

With the highly increasing trend of computational and processing power of the new generation programmable VLSI logic circuits, the fault tolerance problem involves huge problems for designer engineers involved in hardware systems development. In actual stage of technological level in microelectronic sciences, the traditional fault detection methodologies seem to be very inefficient and expensive. The alternative for these problems was inspired from living biological organisms, which are provided with remarkable surviving and fault-tolerance properties. As it known, through cooperation of a huge number of elements called cells, the biological organisms involve nearly perfect self-organization, self-reproduction, and fault tolerance properties in a well organized hierarchical mechanism.

The researchers from microelectronic sciences have early discovered the implementing possibilities of biological organisms’ properties on modern VLSI systems. In this reason basic concepts from cellular embryonic theory are often used for digital systems design and development. Therefore terms like, artificial cell and artificial organism are key concepts in development and implementation of bio-inspired hardware systems.

2. BIO-INSPIRED DIGITAL SYSTEMS DEVELOPMENT STRATEGIES

The international research efforts in bio-inspired hardware systems (embryonic science) are very intensive and dynamic. This large interest is caused by the problems in the more complex VLSI circuits manufacturing processes, which involve difficulties for designer engineers (manufacturing errors, circuits size, fault tolerance), and the large impact in informatics an microelectronics technologies development (VLSI circuits minimization, nanotechnology scale circuits manufacturing). At international stage two basic models are developed for the bio-inspired digital embryonic systems: the architecture with two-level embryonic structures developed at University of York, England [1], [2], [3], and the architecture with four-level embryonic structures developed at
the Swiss Federal Institute of Technology [4], [5].

Taking into account the differences between the real world, biological- and digital systems, in the Logic Systems Laboratory from Swiss Federal Institute of Technology, EPFL Lausanne, it was developed a bio-inspired system architecture, founded in four level of organizing, as is shown in figure 1 [4], [6].

![Embryonic System](image)

Fig. 1. The four level of an embryonic system (Swiss Federal Institute of Technology)

This is a POE (Phylogeny, Ontogeny and Epigenesis) embryonic system developed by researcher E. Sanchez, in analogy with the evolutionary processes of the biological systems. [4], [6]. According to this model, a population is composed from a finite number of organisms. In analogy with the living organisms from biological world, an artificial organism has a finite number of cells, operating in a cell-network. Each cell is an autonomous processor (cellular automate) with a special function inside of organism, defined through an instruction set, named the cell’s gene.

3. FPGA-BASED ARTIFICIAL CELL MODEL

The paper presents some research efforts regarding the development of an FPGA-based artificial cell model with a generalized character, in order to reproduce with high fidelity the complex phenomena and interaction rules in bio-inspired hardware systems. In this reason an original structure for the artificial cell is proposed, as is shown in figure 2 [9]. According to this model each FPGA circuit is considered as an artificial cell with 4 lattices capable for full operating in a bi-dimensional network through specially defined data and control buses. Each lattice of the artificial cell has the same number of input/output bits and configuration structure, with the same operation functions. For example, the upper-lattice of the artificial cell is with the following configuration [7]:

- **UI** \((b_{0ui}, b_{1ui}, b_{2ui}, b_{3ui})\) - the data bus (4 input bits) for receiving information from the upper neighbor cell;
- **CkuI** - the input data bus synchronization clock;
- **UO** \((b_{0uo}, b_{1uo}, b_{2uo}, b_{3uo})\) - the data bus (4 output bits) to send information to the upper neighbor cell;
- **CkuO** - the output data bus synchronization clock;
- **AuI** - signal received from the upper cell \((\text{alive}=1, \text{dead}=0)\)/data transaction enable signal;
- **AuO** - the cell’s internal signal \((\text{alive}=1, \text{dead}=0)\)/data receive enable signal.

The same 12 bit configuration is for the left, right, and down lattice of the artificial cell, too. With the purpose to facilitate the research and modeling process, the artificial cells are organized in macro-groups of cell networks, each with 9 artificial cells, as is presented bellow in figure 3.

![FPGA Model](image)

Fig. 2. The proposed model of an FPGA-based artificial cell.
array, with special function inside of organism, defined through an instruction set (program), and named the cell’s gene. Each cell has a copy of all genes from the organism (operative genome), and as function of the cell’s position inside of organism has one gene operative (the cell’s differentiation properties). In the presented model the operative genome is with 5 genes ($A$, $B$, $C$, $D$, and $E$), and at the same time just one gene is shown active (highlighted in the figure). The cells which don’t show any operative gene are considered spare cells (4 cells from the total of 9 in a cluster).

4. COMMUNICATION STRATEGY AND FAULT-TOLERANCE IN THE FPGA-BASED CELL NETWORK

As it was mentioned before, according to the software model presented in figure 3 each FPGA circuit is considered as an artificial cell with 4 lattices capable for full operating in a bi-dimensional network through specially defined data and control buses. The full network cooperation of cells inside of one cluster (or inside of an organism), is facilitated also through a specially developed network communication strategy [7].

Some aspects of communication rules regarding the fault-tolerance in the cluster are presented in the block diagram given in figure 4. In this first example is considered the case when a fault in the artificial cell_1_1 (matrix codification) occurs. The cell marked in figure with cross-lines is assumed now with a “dead” cell, and the neighboring cells are informed through this new situation through the cell’s special internal signal (cell alive=logical 1, dead cell=logical 0). The information trough the fault occurs will be propagated now toward in the whole cluster.

The propagation way follows the next rules: in the first step the neighbor cell_2_1 and cell_1_2 are informed, in the second step cell_3_1, cell_2_2, and cell_1_3, in the third step cell_3_2, cell_2_3, and at last one the cell_3_3. In the second example given in figure 5, the fault is considered now in cell_2_2. In this case the whole cluster in just two steps will be informed about the new situation: in the first step cells 2_1, 1_2, 2_3, 3_2, and in the second step artificial cells 1_1, 3_1, 3_3, 3_1 (other example: in fig. 6).
5. SIMULATION AND EXPERIMENTAL IMPLEMENTATION OF THE FAULT-TOLERANCE PROPERTIES

As it was early mentioned, the basic goal of the research effort is to model and experiment reconfigurable VLSI systems with the same robustness abilities of living organisms. In this reason, the computer-aided simulations and implementations are focused on reproducing the basic properties and features of biological organisms, in this case especially the fault-tolerance properties. All the simulation and experimental research activity are based on the artificial organism model shown in figure 3. Let’s suppose now in this model a fault occurs in just one of the active cell from the left-upper side cluster (for example the cell which shows the operative gene named \( E \)), expressed with wide cross-lines in figure 7.

As it can be observed from the figure, after the fault detection in the network one of the neighboring spare cells (cell 3_2 or cell 2_3) immediately becomes active, and this cell shows the same operative gene as the “death” cell, respectively the gene named \( E \). In this way the original configuration of the cluster (with active genes: \( A, B, C, D, \) and \( E \)) is recovered once again, and the network with the 9 artificial cell could be considered fault-tolerant, too. The above described process is also expressed with the waveforms sown in the software oscilloscope from figure 8.

![Fig. 7. Fault of one active cell in the network.](image)

![Fig. 9. Fault of four artificial cells in the network.](image)

The fault in the network is evidenced now through the \( \text{Active\_cell.a15} \) signal generated by the decimal coded cell 15, which shows the active gene named \( E \). When this signal is falling-down in logical “0” it means that a fault occurs in the network. But as it can be observed from the figure, exactly in the same moment the \( \text{Active\_cell.a14} \) signal of neighboring spare cell (decimal coded 14) rise in logical “1”. This means that a new cell is activated, and the fault from the network were eliminated. With other words the network now is cicatrizated, as a result of the above described self-healing process.

More experiments can be followed in figures 9 and 10, when a complex situation with 4 artificial cell faults is experimented during the simulation process.

The most complex situation is achieved when a fault with all the active cells in the
cluster is experimented (figure 11). In this special situation for the network cicatrisation just only the 4 spare cells can be used. But as it is known, they are not enough for the whole cluster regeneration process, so in this reason all the cluster is considered faulted, and declared as a “dead” cluster, marked with wide cross-lines in figure 11. This extreme situation in the numerical simulation process is indicated in figure 12 with the Active_cells.alv_cluster_2_1 signal falling down from logical “1” in logical “0”.

The above presented simulations and software implementation results were tested through careful experimentations. Figure 13 shows the laboratory prototype development system used for the artificial cell hardware model implementation on a Digilent’s Basys board [8], [9]. This is an integrated circuit development platform based on a Xilinx XC3S100E FPGA, including the following features: 100,000 gate XC3S100E FPGA, JTAG programming port, XCF02S Xilinx Platform Flash ROM to store FPGA configurations, large collection of I/O devices including 8 LEDs, 4-digit 7-segment display, 4 pushbuttons, 8 slide switches, PS/2 and VGA ports, and user settable oscillator (25/50/100MHz) [9]. With these features the Digilent Basys board provides an inexpensive, robust, and easy-to-use platform, very suitable to implement various industrial control strategies. The board works seamlessly with all versions of the Xilinx ISE tools, including the WebPack tools [9].

Some experimental results obtained with this hardware configuration are given through the waveforms shown in figure 14. Based on Xilinx ISE 9.1 tools and ISE documentation, the results were carried out using VHDL. The developed test software uses the primitive design elements that comprise the Xilinx Unified Libraries for the Virtex-4 architecture [9].
6. CONCLUSION

The proposed models and artificial structures can be a support for future developments in bio-inspired hardware systems, in order to found the theoretical basics, the design models or development methods of this new science domain named the embryonic systems. The basic challenge and application of these researches is to experiment bio-inspired VLSI systems with fault-tolerant and self-healing abilities, as main hardware structures included in high security process control and industrial applications.

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REFERENCES


SZÁSZ Csaba
Virgil CHINDRIȘ
Faculty of Electrical Engineering
Technical University of Cluj-Napoca
15, C. Daicoviciu St.
RO-400020 Cluj-Napoca
Email: Csaba.Szasz@edr.utcluj.ro