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A POEtic Architecture for Bio-Inspired Hardware

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Abstract

The implementation of bio-inspired systems in hardware has traditionally been more a matter of artistry than of method. The reasons are multiple, but one of the main problems has always been the lack of a universal platform, of a standardized architecture, and of a proper methodology for the implementation of such systems.
The ideas presented in this article are the first results of a new research project, "Reconfigurable POEtic Tissue". The goal of the project is the development of a hardware platform capable of implementing systems inspired by all the three major axes (phylogenesis, ontogenesis, and epigenesis) of bio-inspiration in digital hardware.
A novel cellular architecture, capable of exploiting the main features of the future POEtic tissue and compatible with a relatively automatic design methodology, is then presented.

Introduction

The implementation of bio-inspired systems in silicon is quite difficult, due to the sheer number and complexity of interesting biological mechanisms. Most approaches exploit a very limited set of biologically-plausible mechanisms to solve a given problem, but often cannot be generalized due to the lack of a *methodology* in the design of bio-inspired machines and of *architectures* capable of implementing a wide range of bio-inspired mechanisms.
The aim of this work is to present some of the preliminary ideas developed in the framework of a new three-year research project, called "Reconfigurable POEtic Tissue" (or "POEtic" for short) [8], recently started under the aegis of the Information Society Technologies (IST) program of the European Community, involving the Swiss Federal Institute of Technology in Lausanne, Switzerland, the University of York, England, the Technical University of Catalunya (UPC), Spain, the University of Glasgow, Scotland, and the University of Lausanne, Switzerland.
The goal of the project is to address, at least partially, the above issues through the development of digital hardware, and more precisely of a *computational substrate*, specifically designed for the implementation of multiple bio-inspired approaches on a single platform.

The POE Model

Biological inspiration in the design of computing machines finds its source in essentially three biological models [7]: *phylogenesis* (P), the history of the evolution of the species, *ontogenesis* (O), the development of an individual as directed by his genetic code, and *epigenesis* (E), the development of an individual through learning processes influenced by the environment.
On the *phylogenetic axis* we find systems inspired by the processes involved in the evolution of a species through time. The process of evolution is based on alterations to the genetic information, occurring through two basic mechanisms: *crossover* and *mutation*. Both these mechanisms are, by nature, non-deterministic, which represents both their strength and their weakness.
Evolutionary algorithms are usually applied to problems which are either too ill-defined or intractable by deterministic approaches. Not guaranteed to find the best solution to a problem, they can often find an "acceptable" solution more efficiently than deterministic approaches, and have proven their use in hardware design (e.g., [1]).
The *ontogenetic axis* concerns the development of a single multi-cellular organism. This process exploits very specific mechanisms to direct the *growth* of the organism. Cells divide, each offspring containing a copy of the genome (*cellular division*) and acquiring a functionality (e.g., liver cell) depending on its position (*cellular differentiation*). Every cell contains the blueprint for the entire organism (the genome), and thus can potentially replace any other cell [6], providing the possibility of *healing* (self-repair).
The Embryonics project [4][5] is one of the few research efforts in this area. A part of ontogenesis, *morphogenesis*, has been the subject of research [3], and the concept of *development* is also attracting growing attention [2].
The *epigenetic axis* concerns those processes and structures of an organism, such as the nervous or the immune systems, that are directly affected by the environment. The size of the genome does not allow it to completely describe the structure of an adult organism, and the only possible source of additional information for the development of an organism is the environment.

Epigenetic mechanisms have already had considerable impact on hardware design in the form of *artificial neural networks* (ANNs), two-dimensional arrays of massively-interconnected processing elements (the neural cells). ANNs cannot be expected to perform correctly for all input patterns, but have proved their worth in applications such as voice or character recognition, where a limited margin of error is acceptable.

The POEtic Project

The aim of the POEtic project is the development of a computational substrate optimized for the implementation of digital systems inspired by all of the three above-mentioned models. The POEtic tissue is a self-contained, flexible, and physical substrate designed to interact with the environment through spatially-distributed sensors and actuators, to develop and adapt its functionality through a process of evolution, growth, and learning to a dynamic and partially unpredictable environment, and to self-repair parts damaged by ageing or environmental factors in order to remain viable and perform the same functionality.
Following the three models of bio-inspiration, the POEtic tissue will be designed as a three-layer structure (Figure 1):

- The phylogenetic model acts on the genetic material of a cell. Typically, it could be used to find and select the genes of the cells for the *genotype layer*.
- Ontogenesis concerns the development of the individual, and thus the *mapping or configuration layer* of the cell, implementing cellular differentiation and growth. In addition, it has an impact on the system for self-repair.
- The epigenetic model modifies the behavior of the organism during its operation, and is therefore best applied to the *phenotype layer*.

Defining separate layers for each model allows the user to decide whether to implement any or all models for a given problem, and lets the structure of each layer be adapted to the model. This is achieved by implementing the cells on a *molecular substrate*, a surface of programmable logic. In fact, each of the corresponding algorithms is well suited for a particular class of problems. For example, artificial evolution is known to be competitive for non-linear and discontinuous problem domains; learning processes can adapt on a much faster time scale, while ontogenetic processes offer the possibility of fault-tolerance under changing and critical circumstances.
Finally, our tissue presents two innovative hardware-oriented aspects: a *cellular structure* with a full genome for every cell, and a *layered hardware organization* that matches the three axes of bio-inspiration.

Cellular structure

Each cell in the POEtic tissue contains the entire "genome" for the whole tissue. This solution increases the robustness of the system by making it completely local and allowing individual cells to reconfigure their function for growth, self-replication, and self-repair (ontogenesis).
The ontogenetic concept of growth has been largely ignored in the past, for obvious reasons: growth implies the "creation" of new material during the lifetime of an organism, a feature that remains impossible to this day in the world of electronics. However, while the silicon substrate of an electronic circuit cannot grow, a reconfigurable circuit like our POEtic tissue allows its function to be modified at runtime, and thus a growth process based on information rather than matter.
The process of growth is based on cellular division and on cellular differentiation. From the standpoint of both biological organisms and electronic circuits, these two processes are made possible by the existence of the complete plan of the organism (the genome) in each cell. Each cell can specialize to perform a unique function by "executing" only a part of the genetic program depending on its position This differentiation allows multi-cellular organisms, and the POEtic tissue, to display behaviors of a greater complexity than those of single-cell organisms.
Finally, biological multi-cellular organisms can tolerate significant damage. Their "fault-tolerance" is based on a *set* of complex systems, from the organism-wide immune system to single-cell error correction. The POEtic tissue will include a hierarchy of fault-tolerance mechanisms, acting automatically with little or no user intervention.

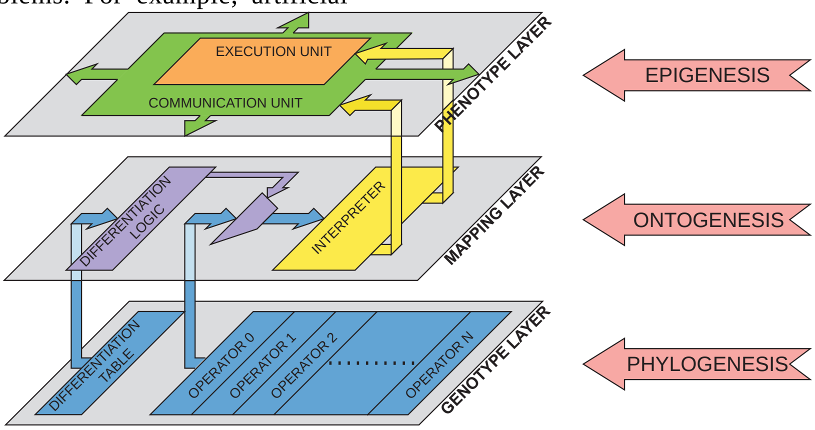

Figure 1: The three organizational layers of the POEtic project.

Layered organization

As mentioned, the POEtic tissue is organized in three hardware layers that match the three main axes of biological organization (Figure 1). The hardware structure of each layer is specific to its role (e.g., the genotype layer will be mainly storage). The explicit distinction in three layers will allow the study and implementation of complex genotype-to-phenotype mappings that can exploit the growth and reconfiguration properties of the tissue.

The mapping between genotypes and phenotypes in evolutionary systems is usually a one-to-one function that does not capture the complex, but highly regulated, mechanisms of gene expression that characterize the development of biological organisms, barely supports the creation of genetic building blocks that could be exploited by crossover operators, and is not scalable to large structures, as the length of the genotype is proportional to the complexity of the phenotype. Our tissue, will provide a substrate that naturally supports the implementation in the configuration layer of smarter and more biologically inspired mechanisms of gene expression.

Finally, the three distinct hardware layers allows the implementation of different bio-inspired mechanisms of self-organization, allowing, for example, to implement neuronal structures without growth or evolution, or conventional fault-tolerant systems deprived of adaptation.

A Bio-Inspired Architecture

Nature is *change*. Adaptation and specialization are key features of all biological organisms. As a consequence, no bio-inspired architecture can be rigid, but must rather be able to adapt and specialize depending on the desired application. This requirement can be satisfied by exploiting *reconfigurable logic* (e.g., FPGAs) POEtic architectures will then consist of two-dimensional arrays of *cells*, where each cell is a small, fully reconfigurable processing element, specialized for the application and for the bio-inspired mechanisms to be implemented.

The role of the tissue, then, is to provide a *molecular substrate* for the implementation of the cells: as organic cells are constituted by molecules, so our artificial cells will be constituted by the programmable logic elements of our POEtic circuit. All three layers of the POEtic systems will all be implemented on this substrate.

The *genotype layer* is conceptually the simplest of the three layers of the tissue. It contains the genetic information of the organism (Figure 2):

- A *set of operators*, which define the set of all possible functions for the cell. The operators depend on the application (e.g., initial neuron parameters and weights).
- A *differentiation table*, used to determine which operators will be implemented in which cell. The table contains a *compact*, possibly redundant, representation of the operators to be implemented by the cells, to which evolutionary mechanisms will be applied.

The key feature of the genotype layer lies in the presence of a set of *dedicated connections*, used to provide access to the differentiation tables of all the cells in the system via an e*xternal microcontroller*, whose function is to apply user-defined evolutionary mechanisms to the tables' contents.

The *configuration layer* of the POEtic systems is designed to implement the processes of cellular differentiation and cellular division (growth), the bases of the ontogenetic model (the fault-tolerance aspect of the model is in general distributed throughout the layers of the array)

In its simplest conception (Figure 3), the configuration layer selects which operator will be implemented depending on a set of coordinates, incremented in each cell and transmitted along both axes. However, this approach is only a very basic solution to achieve cellular differentiation, and does not exploit many of the most interesting features of the development process. More complex differentiation mechanisms, based for example on L-systems [3] and on protein gradients, are under study.

The *phenotype layer* is probably the most application-dependent layer. If the final application is a neural network, the phenotype layer of the cell will consist of an artificial neuron. In particular, the POEtic project will concentrate on *spiking neurons* [8], but this choice does not imply that the tissue will be limited to such a model.

To be universal, however, the POEtic tissue will not be limited to neural-like cells, and a more general-purpose phenotype architecture is being researched. For example, a candidate architecture is outlined in Figure 4. It consists of:

- An execution unit, consisting of a set of application-dependent *resources* (e.g., adders, counters), defined by the user and accessed through a set of I/O ports.
- A communication unit that, in view of the massive connectivity of bio-inspired systems, will probably have to rely on *serial communication*.

This kind of architecture has two main advantages, in the context of the POEtic project: it can support specialization through the adaptation of the resources to the application and it can be integrated in a *design environment*.

A typical application-driven design flow for a bio-inspired system in such an environment could then be:

- Based on the application, the user defines the models to be implemented in the system. The user then accesses a *library of operators* and selects those that will be required by the application(e.g., a family of neurons).
- The environment will then (if desired) automatically integrate the desired operators into a *totipotent cell*, that is, a processing element capable of realizing any of the functions. Other optional ontogenetic features, such as growth and self-repair, can be automatically added.
- Finally, the design environment assembles the cells into a two-dimensional array, integrates the I/O modules, and generates a configuration for the programmable logic.

The key feature of such an environment is the *automatization* of a large part of the design flow. The user need only decide which bio-inspired models and operators are required by the application.

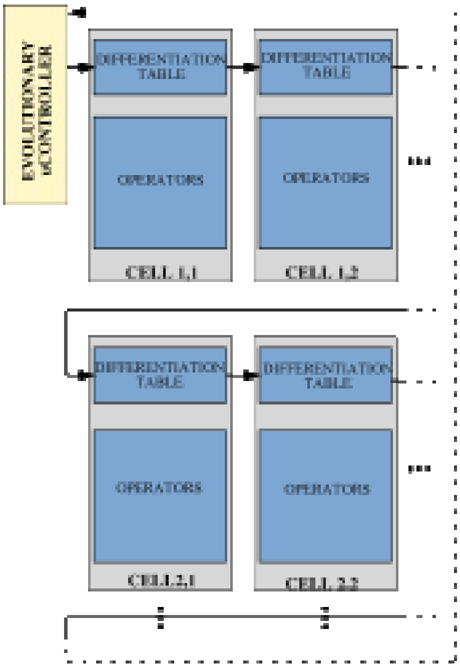

Figure 2: The genotype layer in an array of cells and the evolutionary controller.

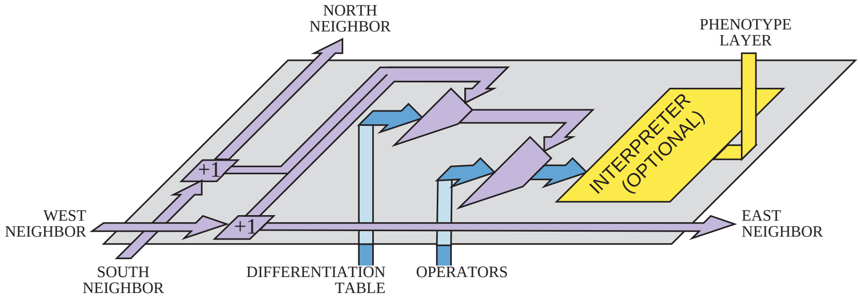

Figure 3: A possible structure for the configuration or mapping layer.

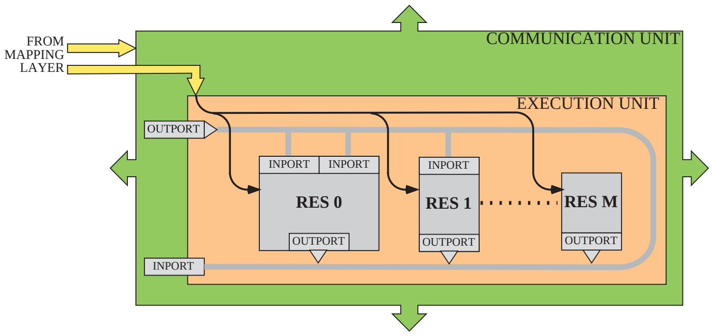

Figure 4: Outline of a possible architecture for the phenotype layer.

Conclusions

The POEtic project proposes an hardware substrate capable of implementing bio-inspired systems. In other words, it wants to develop the *molecules* necessary for the development of cellular systems. The usefulness and the practicality of the molecular surface will obviously be validated on a number of bio-inspired applications, ranging from neural networks to music synthesis. And beyond, it is our hope that the circuits created in this project will find users well beyond our group.

This article by no means presents the final version of the POEtic system: the project has started only recently, and the ideas presented here are simply the *first* results of our research. We invite all readers to access our website [8], where we regularly post the progress reports and deliverables of the project.

Acknowledgements

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