Hardware Realization of a Bio-inspired POEtic tissue

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Abstract

This paper will present the physical hardware realization of a novel bio-inspired architecture, called POEtic tissue. This electronic tissue provides a platform for the efficient implementation in actual hardware of evolutionary, epigenetic (learning) and ontogenetic (growth, self-repair, self-replication) mechanisms. After a brief introduction the overall organization of the tissue will be presented. Then its main building blocks will be reviewed. Finally, the implementation details of the first hardware prototype of the tissue, constructed in the form of an ASIC, will be outlined. The implementation results demonstrate that the proposed architecture constitutes a good candidate when considering the electronic realization of bio-inspired principles.

1. Introduction

The basic principles driving the organisation of living beings have provided a longstanding inspiration for handling diverse engineering problems, ranging from computer networks planning to navigation management in autonomous robots. From a global viewpoint it can be considered that these basic principles are structured around three main axes: phylogenesis, ontogenesis and epigenesist. Phylogenesis encompasses all the processes that result in what is usually called natural evolution, i.e., the development of living species and populations driven by the pressure exerted by the environment. These processes have produced the huge variety of living being that can be observed on earth. Ontogenesis refers to the development of an individual from the genetic code resulting from the natural evolution, but without any interaction with the environment. The self-repair (healing) and self-test capabilities that can be usually observed in living beings can be considered as ontogenetic mechanism. Finally, the epigenetic mechanisms, also known as learning abilities, permit a given individual to optimally adapt the capabilities determined by its genetic code to the specific features of the environment. Examples of this mechanisms can be observed in the vertebrates in the central nervous system (constituted by a number of synapses much larger than the number of nitrogen bases composing the DNA) or in the immune system.

The three organisation principles have been independently applied to solve engineering problems for more than five decades, and some of them have even resulted in physical realisations. However, due mainly to technology limitations, until recently it has been difficult to integrate them in a holistic way so as to construct what could be called an actual electronic tissue with capabilities inspired on biological systems. A realisation like this would permit to find an efficient solution for a wide range of problems, such as the construction of robust systems to be operated in harsh or remote environments or the development of system with the ability to adapt to unknown environments.

The POEtic tissue [1] constitutes a novel approach for constructing an electronic substrate capable of providing support for the actual hardware implementation of bio-inspired features, like evolution, growth, self-repair, self-replication or learning.

To achieve this goal at the functional level there are several requirements to be fulfilled by the architecture to be conceived for the tissue. These can be summarized as follows:

- Its structure has to be multi-cellular and scalable.
- It has to permit the implementation of phylogenetic (P), ontogenetic (O) and epigenetic (E) mechanisms, separately or in any combination, that constitute the three main axes of biological organization, following the POE model introduced in [2].

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- It has to allow for a massive interaction with the external environment.

This has resulted in a hardware architecture whose internal organization is built on a layered hardware structure resembling the three axes (P, O and E) indicated previously. Next section describes the details of this organization.

2. Organization of the POEtic tissue

Bearing in mind the previous considerations the global organisation that has been designed for the POEtic tissue is depicted in Figure 1.

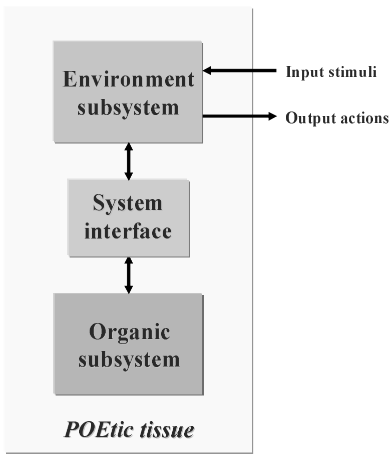

Figure 1. Global organization of the POEtic tissue.

As it can be deduced from this figure, the tissue is composed of three main parts:

- **Environment subsystem:** This is the component of the tissue that is in charge of managing the interaction with the environment. This interaction can be considered at two different time scales: on-line interaction and evolution. The on-line interaction refers to the continuous process by means of which a given individual implemented in the tissue is sensitive to the input stimuli that arrive from the external environment. These stimuli may take the form of any physical magnitude (light, pressure, temperature, …), and after a conditioning and conversion processes are translated into internal signals that may be used by the individual either to extract some knowledge from the environment or to produce an output as a result of some internal processing. These output signals may be later translated, by means of a set of proper actuators, into physical magnitudes that are reverted as output actions to the environment. This on-line interaction constitutes the basic sensor-actuator loop that permits a given individual to adapt its behaviour to the specific characteristics of the environment where it is placed. The second kind of interaction with the environment acts at a population level and exceeds the lifetime of an individual. In this case the sensor-actuator loop is used to define the basic substrate (the genome) of the individuals that are capable of adapting its behaviour to the environment in the most efficient way according to a given fitness measure.
- **Organic subsystem:** It is in charge of implementing the behaviour of an individual, following the principles described by the innate information that has resulted from the evolutionary process. Therefore, it is the goal of this system to permit the development (ontogenesis) of a given functionality from the information stored in a genome, and also to permit the adaptation (epigenesis) of this functionality according to the stimuli received from the environment.
- **System interface:** This element will allow for an efficient communication between the environment and the organic subsystem of the tissue. It also constitutes the substrate that will provide the basic mechanisms that will permit the scalability of the tissue.

The environment subsystem of the POEtic tissue has been built around a custom 32-bit microprocessor with an efficient and flexible system bus and several custom peripherals. The reason for using a centralised system to carry out evolutionary processes is motivated by the fact that, even if evolution acts on a population of individuals, it is easier from an implementation point of view to have a global unit that evaluates the fitness of the individuals and determine those from which the next population has to be constructed. Therefore, the functionality of the individuals will be implemented in the organic subsystem, but it is the microprocessor that constitutes the core of the environment subsystem that will drive the basic steps of the evolutionary process, as well as the interaction of the individuals with the environment. Additionally, the use of a programmable unit to implement the phylogenetic mechanisms of the tissue will permit to test and develop different evolutionary strategies, since this will imply just an update of the software executed by the microprocessor. Finally, this alternative will largely simplify the management of the acquisition/conversion units that are required to handle the sensor-actuator loop needed to complete the epigenetic and phylogenetic processes to be implemented by the tissue.

Regarding the organic subsystem, one of the main requisites that were considered during its development was the support for the implementation of virtually any type of cell. To attain this requirement the organic subsystem is organised around a regular bi-dimensional grid of elementary units, called molecules. A molecule is a simple piece of configurable digital hardware (a four-input lookup table –LUT, a register and a switch box) that may interact with its direct four neighbours. Molecules may be configured to provide a given digital function, and by combining molecules it is possible to construct virtually any type of digital cell. An organism is then able to exhibit a given functionality by combining as many cells as required. A novel dynamic interconnection mechanism at the cellular level has been designed for the organic subsystem. This strategy permits the cells of an organism to dynamically establish connections during its development process, as well as during its lifetime as forced by the interaction with the environment. This dynamic routing strategy, that is absent in classical hardware platforms, is one of the essential elements that enables the efficient implementation of ontogenetic and epigenetic mechanisms.

The organisation of the organic subsystem allows for a layered hardware structure that resembles the principles behind the three main axes of biological organisation. At the beginning of the lifetime for a given organism the organic subsystem is just a sea of regular and still unspecialised molecules. During development the molecules organise into cells, and once the cells arise the genome of the organism is interpreted to provide the individual cell configurations required to create a function. After this configuration process is completed the cells connect themselves autonomously using the dynamic routing principle that has been included in the organic subsystem. At this time the organism shows the innate basic behaviour that was determined during the evolutionary process, and therefore it is the end of the initial genotype to phenotype translation process. Since cells are composed of configurable elements (the molecules) and they can change their connectivity pattern autonomously at any time, epigenetic processes may take place as required by the specific interaction of the organism with the environment.

Apart from the environment and organic subsystems included in the POEtic architecture, there is a fundamental building block that will permit the tissue to exhibit its inherent features: the system interface. The primary goal of this component is to allow for an efficient interaction between the environment and the organic subsystems. Furthermore, the system interface will cope with the scalability issues of the tissue. Due to technology and cost constraints, when a POEtic unit is implemented in silicon there is a limit for the amount of resources that constitute the organic subsystem. For this reason, the system interface has to be designed so as to permit the efficient communication of as many POEtic units as required in order to handle a given application. The system interface has been built around an optimised version of a standard SOC (System On a Chip) bus architecture, the AMBA bus [3]. Apart from allowing for the construction of an organic subsystem of virtually any size, the system interface will permit to construct an actual distributed sensor/actuator platform, as is common to most living beings.

3. Organic subsystem

As it was explained previously, the organic subsystem is constituted by a regular array of basic building blocks, called molecules, that allow for the implementation of any logic function. This array constitutes the basic substrate of the system. On top of this molecular layer there is another one that implements dynamic routing mechanisms between the cells that are constructed combining the functionality of different molecules. Therefore, the physical structure of the organic subsystem can be considered as a two-layer organisation, as depicted in Figure 2.

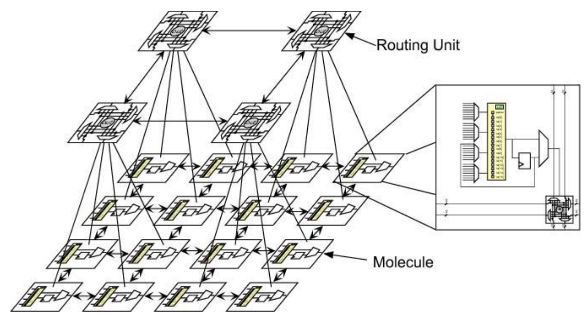

Figure 2. Structural organisation of the organic subsystem.

A molecule is the smallest programmable element of the POEtic tissue. It is mainly composed of a flip-flop (DFF), and a 16-bit look-up table (LUT). Eight modes of operation are supplied to ease the development of applications that need cellular systems and/or growth and self-repair. The LUT is composed of a 16-bit shift register that can be split in two, used as a shift register, or as a normal look-up table.

The eight operational modes supported by a molecule can be briefly described as follows:

- In **4-LUT** mode, the 16-bit LUT supplies an output, depending on its four inputs.
- In **3-LUT** mode, the LUT is split into two 8-bit LUTs, both supplying a result depending on three inputs. The first result can go through the flip-flop, and is the first output. The second one can be used as a second output, and is directly sent to the south neighbour (can serve as a carry in parallel operations).
- In **Comm** mode, the LUT is split into one 8-bit LUT, and one 8-bit shift register. This mode could be used to compare a serial input data with a data stored in the 8-bit shift register.

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- In **Shift Memory** mode, the 16 bits are used as a shift register, in order to store data, for example a genome. One input controls the shift, and another one is the input of the shift memory.
- In **Input** mode, the molecule is a cellular input, connected to the inter-cellular routing plane. One input is used to enable the communication. When inactive, the molecule can accept a new connection, but won't initiate a connection. When active, a routing process will be launched at least until this input connects to its source. A second input selects the routing mode of the entire POEtic tissue.
- In **Output** mode, the molecule is a cellular output, connected to the inter-cellular routing plane. One input is used to enable the communication. When inactive, the molecule can accept a new connection, but won't initiate a connection. When active, a routing process will be launched at least until this output connects to one target. Another input supplies the value sent to the routing plane, as so to another cell.
- In **Trigger** mode, the 16-bit shift register should contain "000...01" for a 16-bit address system. It is used by the routing plane to synchronize the address decoding during the routing process. One input is a circuit enable, that can disable every DFF in the tissue, and another one can reset the routing, and so start a new routing. Only one molecule in trigger mode is to be included in a cell to permit the dynamic routing process to work properly.
- In **Configure** mode, the molecule can partially configure its neighbourhood. One input is the configuration control signal, and another one is the configuration shifting to the neighbours.

Long distance inter-molecular communication is possible by the way of switch boxes. Each switch box consists of eight input lines (two from each cardinal direction) and eight corresponding output lines, and are implemented with eight inputs multiplexers. Two outputs are sent into each of the four neighbours of the molecule, as shown in Figure 3.

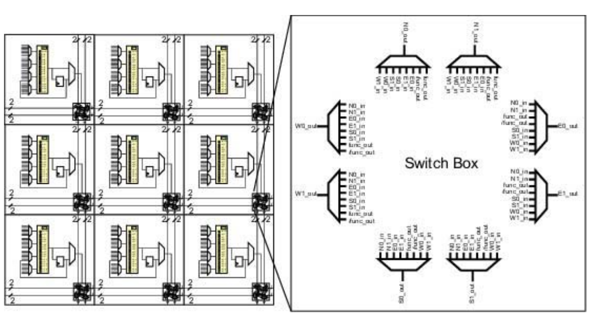

Figure 3. Inter-molecular communication and detail of a switch box.

The second layer of the organic subsystem implements a dynamic routing algorithm [4] to allow the circuit to create paths between different parts of the molecular array. The dynamic routing system is designed to automatically connect the cells' inputs and outputs. Each output of a cell has a unique identifier, at the organism level. For each of its inputs, the cell stores the identifier of the source from which it needs information. A non-connected input (target) or output (source) can initiate the creation of a path by broadcasting its identifier, in case of an output, or the identifier of its source, in case of an input. The path is then created using a parallel implementation of the breadth-first search algorithm [5]. When all paths have been created, the organism can start operation, and execute its task, until a new routing is launched, for example after a cell addition or a cellular self-repair.

Our approach has many advantages, compared to a static routing process. First of all, a software implementation of a shortest path algorithm, such as Dijkstra's [6], is very time-consuming for a processor, while our parallel implementation requires a very small number of clock cycles to finalize a path. Secondly, when a new cell is created it can start a routing process, without the need of recalculating all paths already created. Thirdly, a cell has the possibility of restarting the routing process of the entire organism, if needed (for instance after a self-repair). Finally, our approach is totally distributed, without any global control over the routing process, so that the algorithm can work without the need of the central microprocessor.

As explained before, the routing layer is made of routing units and the molecular layer of molecules, and one routing unit is connected to four molecules. So an interface between these molecules and the routing unit is necessary to manage the communication. This entity manages the signals going from the molecules to the routing units and in the other direction. So, a third layer, containing these interfaces is present between the routing layer and the molecular layer, as depicted in Figure 4. It could have been implemented directly in the routing units, but this separation between the molecules and the routing units would allow changing the number of molecules connected to a routing unit without modifying the routing unit, but only the interface.

4. Environment subsystem

The main goal of the environment subsystem is to permit interactions (either long- or short-term) between the environment and the organic subsystem. For this purpose, the environment subsystem is constituted by two main building blocks: a custom 32-bit microprocessor and an acquisition subsystem.

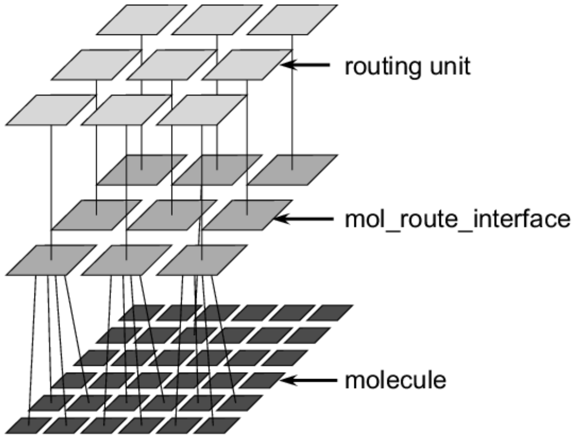

Figure 4. The tissue is actually composed of 3 layers: the molecules, the interface, and the routing units (not all connections are shown between molecules and interfaces).

The microprocessor is in charge of implementing the evolutionary mechanisms that provide phylogenetic features to the POEtic tissue. Furthermore, it is in charge of managing the overall control of the organic subsystem, including the configuration of its molecules.

The acquisition subsystem is in charge of handling the direct interaction with the environment, by controlling the signals that drive the external sensors and actuators. The input signals coming from sensors are distributed to the cells that are physically present in the organic subsystem, while the signals resulting from the cells are sent to the external actuators.

The main features of the POEtic microprocessor can be summarised as follows:

- Every instruction is executed in one clock cycle.
- The pipeline of its sequencing unit is divided in five stages: Fetch, Decode, Execute, Memory and Write-back. All the possible hazard types (data, control and structural) are handled internally in the sequencer using pipeline stalling, data forwarding and instruction pre-fetching mechanisms.
- The length of all the instructions is 32 bits.
- The operation code is 6 bits wide.
- The processors architecture is based in a 3-port (2 read, 1 write) 32 x 32-bit register file. This permits the development of an instruction set where every instruction can process in one clock cycle two source operands and provide the result in a target operand that may be different from the source ones.
- The communication between the processor core and its memory and/or peripherals is based on a LOAD/STORE scheme.
- The communication between the microprocessor and the environment is carried out using a standard AMBA interface. The microprocessor includes an internal AHB controller and an APB bridge that permits to use as many peripherals as desired within the internal APB bus.
- The microprocessor may have a dedicated local memory block for program and data. Any external memory can be used by attaching it to the external AHB bus. Currently two 16-bit timers and an 8-bit Booth multiplier have been included as peripherals of the microprocessor.
- The microprocessor is able to handle up to 5 interrupt sources. The priority for the interrupts can be set by means of a mask. A dedicated internal stack has been included, so as to permit the sequencer to handle up to 32 nested interrupts.
- The ALU of the microprocessor includes a pseudo-random number generator, so as to facilitate the implementation of evolutionary and genetic algorithms. This unit has been implemented using a 32-bit LFSR (Linear Feedback Shift Register). Specific instructions permit to load this register with an initial seed and to read its value at any time.

The overall organization of the microprocessor is depicted in figure 5.

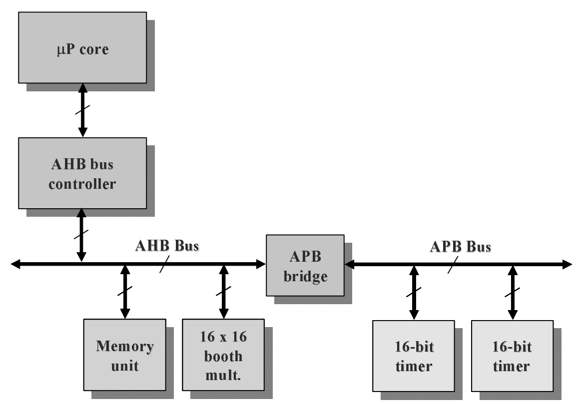

Figure 5. Internal organisation of the POEtic microprocessor

The interaction of the microprocessor with internal and external interfaces, as well as with the memory units is organised around a careful hierarchical design of its memory map. The memory map of the microprocessor is divided in two main sections: Internal memory unit and AHB/APB bus. The internal memory unit space is divided also in two main sections: Program memory and data memory. Figure 6 depicts the organisation of the memory map of the microprocessor.

As it can be deduced, the memory unit occupies the first 64 Kwords (in our case a word is 32-bit wide) of the memory map, from which the first 1 Kwords correspond to the program memory.

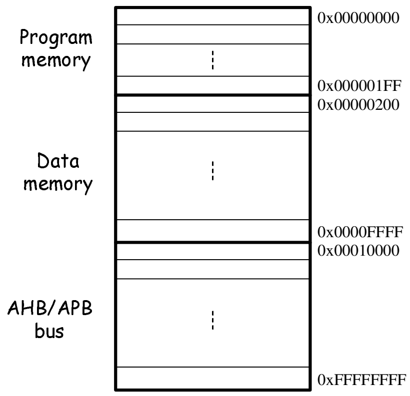

Figure 6. Organisation of the memory map of the microprocessor.

It is important to consider that the start and end addresses of every section can be programmed by the user. The sizes depicted in Figure 6 correspond just to the values used during the prototyping phase, but they can be modified (just by setting the proper parameters in the VHDL synthesisable code) to accommodate the needs of the application.

This organisation allows for a flexible management of the system peripherals, since they are handled basically by means of simple read and write memory accesses.

The management of peripherals within the AHB and APB buses can be configured easily by modifying some parameters in the VHDL synthesisable code. Specifying the following parameters sets the configuration for a given peripheral:

- Start address of the peripheral.
- End address of the peripheral.
- Identifier of the peripheral within the system.
- Peripheral enabled or disabled.

The main goal of the acquisition subsystem is to permit the interaction of the POEtic tissue with its external environment. This interaction is based on a sensor-actuator loop that implies the acquisition of signals from the external environment, the processing of these signals by the tissue and the generation of a response that is reverted to the environment.

In order to permit the flexible control of this sensor-actuator loop the acquisition subsystem is composed of 16 bidirectional lines that can be used independently as inputs or outputs. Every line may have a register in order to facilitate synchronisation tasks. Additionally, every line has a routing unit like those described previously. These routing units are directly connected with the routing units associated with the organic subsystem, thus allowing for the direct communication between the cells implemented in the POEtic tissue and the external sensors/actuators.

The acquisition subsystem is physically placed in the AHB section of the microprocessor bus, and will act as an AHB slave. This permits a flexible management of this unit through the microprocessor.

5. System interface

As it was explained in previous sections, it is the holistic integration of the organic and environment subsystems that permits the POEtic tissue to exhibit its phylogenetic, ontogenetic and epigenetic features. This integration is carried out by the system interface that is part of every POEtic chip. The system interface allows also for the efficient communication between POEtic chips, so that the final tissue is completely scalable.

A dedicated unit included in every POEtic chip accomplishes the interface between the environment and the organic subsystems. The overall organisation of this component, called configuration unit, is depicted in Figure 7.

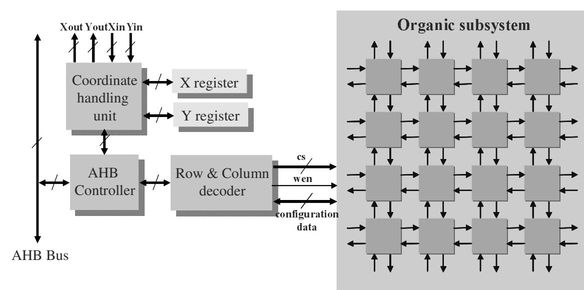

Figure 7. Organization of the configuration unit

As it can be deduced from this figure, the configuration unit is placed on the AHB section of the microprocessor bus, acting as a slave. It contains an AHB controller that permits to manage the bus transfers coming from the microprocessor. In the upper left part of Figure 7 it is possible to observe a component called coordinate handling unit. The goal of this subsystem consists in allowing a single microprocessor to manage as many organic subsystems as required to implement a given organism in the tissue.

The interaction between the microprocessor and the organic subsystem is managed using a parallel interface composed of the ***configuration data*** and ***cs*** buses and the ***wen*** signal depicted in Figure 7. Since every molecule contains 76 configuration bits and the microprocessor uses a 32-bit system bus, the configuration map of the molecules is organised in three 32-bit slices, meaning that 3 chip select (***cs***) signals will be required per molecule. The ***wen*** (write enable) signal indicates if the access to a given molecule's configuration slice corresponds to a read or write process. Finally, the 32-bit wide ***configuration data*** bus contains the data to be read/written from/to the configuration slice of a given molecule.

The decoder included in the configuration unit permits to carry out partial reconfiguration processes in the organic subsystem. In this way, the microprocessor can set a specific row and column masks, so that all the molecules included in the rectangular area defined by this mask will experiment the subsequent read or write access. This means that the ***cs*** signals are in fact decoded from the internal registers that store the row and column masks. This feature also accelerates the configuration process in the case it is necessary to configure in the tissue cells with the same functionality.

It is important to bear in mind that one of the most important features to be attained by the POEtic architecture is the possibility of creating an actual scalable tissue. This means that a given environment subsystem should be able to interact with an organic subsystem as large as required by the actual organism to be implemented in the tissue. However, due to technology and costs constraints, the size of the organic subsystem in a given chip is limited. As a consequence, a flexible and as transparent as possible mechanism has to be included in the tissue, so that by combining different POEtic chips it will become possible to create a tissue as large as desired.

The coordinate handling unit is in part responsible for these scalability features. In an actual POEtic tissue its physical layout will be composed of a bi-dimensional array of POEtic chips, each of them containing an environment subsystem, an organic subsystem and a system interface.

The environment subsystems of all the POEtic chips will share the same AMBA bus. In this array only one environment system acts as a master for the tissue, and this is signalled by using a dedicated input in the POEtic chip.
The organic subsystems included in every chip interfaces directly at the molecular and at the routing layer levels with the four direct neighbours in the array. At the same time, the configuration unit of a given chip is connected with those of its four direct neighbours by means of two serial lines in every direction (***Xout***, ***Yout***, ***Xin***, ***Yin*** buses in Figure 7).

Therefore, upon a startup a given environment subsystem recognises that it is the master in the tissue, and as a consequence it sends an init command to its configuration unit. This will start a coordinate propagation process through the tissue, so that after several system clock cycles every POEtic chip is identified by a (X,Y) coordinate pair. The X and Y coordinates assigned during this initialisation phase are part of the address space reserved for a given configuration unit. For instance, in the sample memory map presented in Figure 6 the address space for the AHB/APB buses starts at 0x00010000. Let's consider that the POEtic tissue is composed of a 16x16 array of POEtic chips, and the memory map is organised so that the configuration units are placed at the end of this map. In this case the memory map for the organic subsystem is 1_X_Y_0000_0000_0000_0000_0000_000. This means that we permit an 8M-word addressing space for the organic subsystem included in every POEtic chip (i.e., more than 2 million molecules per chip).

The X and Y coordinates of the configuration unit are shared with the acquisition subsystem. This also permits the master environment subsystem to manage as many acquisition subsystems as present in the actual POEtic array. This finally allows for the construction of a tissue with actual distributed sensing/actuating capabilities.

6. Implementation

Once the architecture of the POEtic tissue has been defined, an ASIC prototype has been designed in order to verify all the features to be exhibited by the tissue. This ASIC prototype has been manufactured using a CMOS 0.35 μm 1P-5M technology. Figure 8 shows the layout of this prototype.

The left part of the figure is occupied by the microprocessor and the system interface. In the right section of the layout three components can be identified. Each of them contains a group of four molecules and a routing unit.

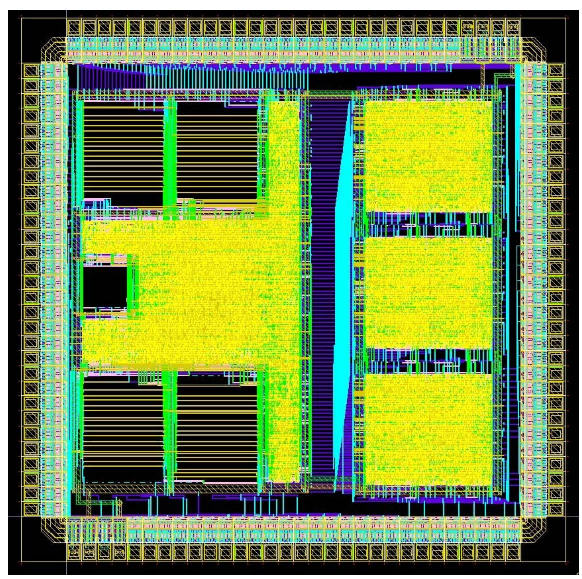

Figure 8. Layout of the POEtic chip prototype

The register file of the microprocessor has been implemented using four 32x16-bit dual-port synchronous RAM blocks (the black boxes placed on the top and bottom sections of the microprocessor). A 32x10-bit single-port synchronous RAM (the black box in the center of the microprocessor section) has been used to implement the internal stack of the microprocessor. The goal of this stack is to save temporarily the interrupt mask and the status register upon arrival of an interrupt.

The total area occupied by this hardware prototype is 13 mm^2.

Specific development tools have been created to permit the efficient use of the POEtic chips. An assembler (derived from a customization of the WinTim32 meta-assembler [7]), a C compiler (obtained from a customization of the LCC meta-compiler [8]) and a simulator are available for the POEtic microprocessor. A simulation tool for the organic subsystem has also been developed. This tool has a graphical user interface that facilitates the development of applications to be implemented using the programmable cells that constitute the organic subsystem.

7. Conclusions

This paper has presented a novel hardware architecture, called POEtic tissue, aimed at the physical implementation of bio-inspired models.

The architecture has been conceived so as to permit the realization of phylogenetic, ontogenetic and epigenetic features. It is constituted by three main building blocks: an environment subsystem, an organic subsystem and a system interface.

After reviewing in detail the structure and functionality of the basic components of the system the current status of the first hardware prototype for the POEtic tissue has been explained. This prototype has been designed in the form of an ASIC, and it is intended to demonstrate the basic features to be attained by the final tissue.

Our current work is concentrated in the qualification of the test chip and in the optimization of specific cells of the device (register file and configuration memory for the molecules). These optimizations will be included in the final POEtic chip, that will constitute an efficient platform for the implementation of actual bio-inspired hardware.

Acknowledgements

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