Abstract

In the design of new machines or in the development of new concepts, mankind has often observed nature, looking for useful ideas and sources of inspiration. The design of electronic circuits is no exception, and a considerable number of realizations have drawn inspiration from three aspects of natural systems : the evolution of species (Phylogenesis), the development of an organism starting from a single cell (Ontogenesis), and learning, as performed by our brain (Epigenesis).

These three axes, grouped under the acronym POE, have for the most part been exploited separately : evolutionary principles allow to solve problems for which it is hard to find a solution with a deterministic method, while some electronic circuits draw inspiration from healing process in living beings to achieve self-repair, and artificial neural networks have the capability to efficiently execute a wide range of tasks. At this time, no electronic *tissue* capable of bringing them together seems to exist.

The introduction of reconfigurable circuits called Field Programmable Gate Arrays (FPGAs), whose behavior can be redefined as often as desired, made prototyping such systems easier. FPGAs, by allowing a relatively simple implementation in hardware, can considerably increase the systems' performance and are thus extensively used by researchers. However, they lack plasticity, not being able to easily modify themselves without an external intervention.

This PhD thesis, developed in the framework of the European POEtic project, proposes to define a new reconfigurable electronic circuit, with the goal of supplying a new substrate for bio-inspired applications that bring all three axes into play. This circuit is mainly composed of a microprocessor and an array of reconfigurable elements, the latter having been designed during this thesis. Evolutionary processes are executed by the microprocessor, while epigenetic and ontogenetic mechanisms are applied in the reconfigurable array, to entities seen as multicellular artificial organisms. Relatively similar to current commercial FPGAs, this subsystem offers however some unique features. First, the basic elements of the array have the capability to partially reconfigure other elements. Auto-replication and differentiation mechanisms can exploit this capability to let an organism grow or to modify its behavior. Second, a distributed routing layer allows to dynamically create connections between parts of the circuit at runtime. With this feature, cells (artificial neurons, for example) implemented in the reconfigurable array can initiate new connections in order to modify the global system behavior.

This distributed routing mechanism, one of the major contributions of this thesis, induced the realization of several algorithms. Based on a parallel implementation of Lee's algorithm, these algorithms are totally distributed, no global control being necessary to create new data paths. Four algorithms have been defined implemented in hardware in the form of routing units connected to 3, 4, 6, or 8 neighbors. These units are all identical and are responsible for the routing processes. An analysis of their properties allows us to define the best algorithm, coupled with the most efficient neighborhood, in terms of congestion and of the number of transistors needed for a hardware realization. We finish the routing chapter by proposing a fifth algorithm that, unlike the previous ones, is constructed only through local interactions between routing units. It

offers a better scalability, at the price of increased hardware overhead.

Finally, the POEtic chip, in which one of our algorithms has been implemented, has been physically realized. We present different POE mechanisms that take advantage of its new features. Among these mechanisms, we can notably cite auto-replication, evolvable hardware, developmental systems, and self-repair. All of these mechanisms have been developed with the help of a circuit simulator, also designed in the framework of this thesis.