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Embryonics: Towards New Design Methodologies for Circuits with Biological-like Properties

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ABSTRACT

Embryological electronics or "Embryonics" is a new paradigm for developing digital systems of any complexity, endowed of self-repair and self-reproduction capabilities. Embryonics, which can also be defined as a quasi-biological development of artificial systems, is based on the natural mechanism of development of living multi-cellular beings. Starting with a single mother cell containing the description of the organism in the form of a genome, the final organism is achieved through a succession of cell divisions, occurring with the differentiation of each cell, i.e. a specialization dependent essentially on the physical position of the cell (i.e on its coordinates) in the given space. Theses processes are implemented with the help of circuits having reconfiguration capabilities. Such circuits involve new design methodologies at their application level. They also present biological-like properties thanks to their configuration level.

1. EMBRYONICS

Embryonics, i.e. the quasi-biological development of multi-cellular automata, is based on a *general hypothesis*, which describes the environment in which the development occurs, and on *three characteristics*, which roughly approximate the biological mechanism of cellular development [Mange 94].

1.1 The general hypothesis: the environment

The general hypothesis describes the selected environment: (a) the automaton deals exclusively with the flow of information; the physical material (usually a silicon substrate) and the energy (power supply) are given a priori; (b) the physical space is two-dimensional and as large as desired; (c) the physical space is *homogeneous*, that is connections with their neighbors; only the *state* of a cell (the combination of the values in daughter automaton is identical to the mother automaton.

1.2 The three characteristics

The first characteristic is that of *multi-cellular organization*. The proposed automaton meets all the general hypotheses described before. The cell is essentially a random access memory (RAM) controlled by a small processor: a part of the state of this RAM, called the *gene*, completely defines the permanent operation of the cell. The value of the gene depends only on the position of the cell in the whole automaton. Fig. 1 illustrates the example of a simple artificial organism, an up-down counter detailed later, with nine cells, each cell being defined by a gene.

The second characteristic is that of *cellular differentiation*. Each cell holds the complete description of the organism, i.e. the *genome* (Fig. 2) and computes its gene by extracting from the genome the function which characterizes it. The gene of a cell depends on its coordinates, i.e. on its place within the organism.

The third characteristic is that of *cellular division*. At the beginning (time t0) only one cell, the mother cell, holds the genome of the organism (Fig. 3). After a first division (time t1), two adjacent cells, to the north and to the east, hold a copy of the information of the mother cell.

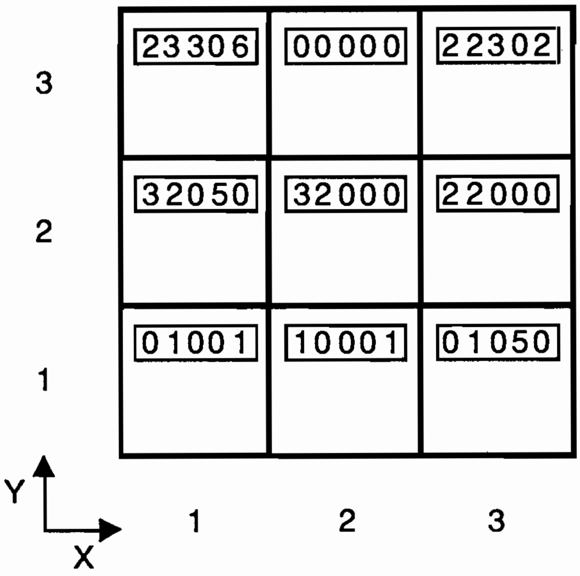


Fig. 1

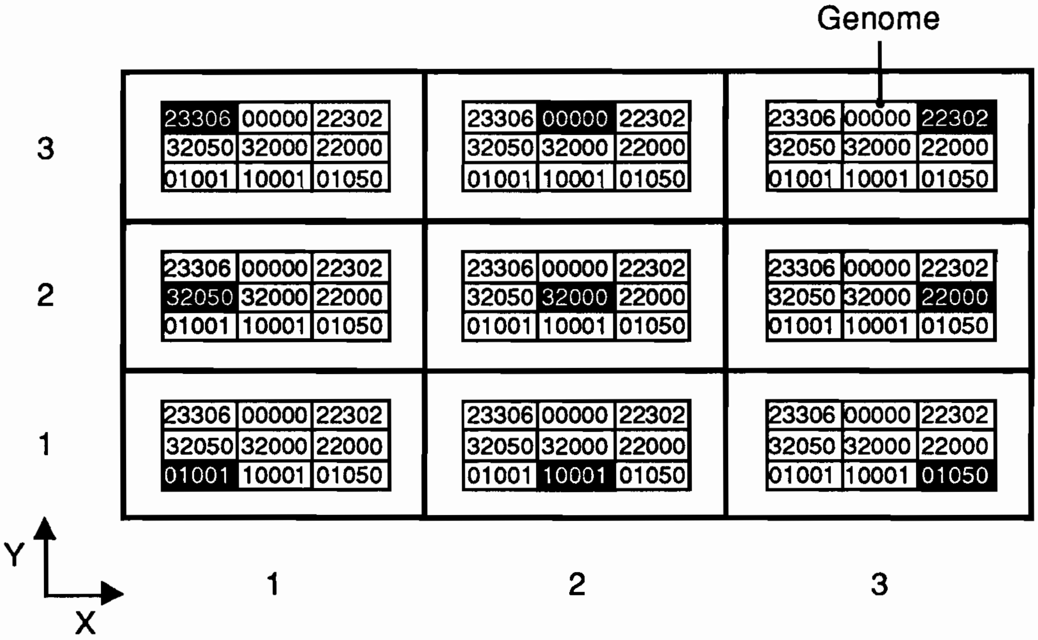


Fig. 2

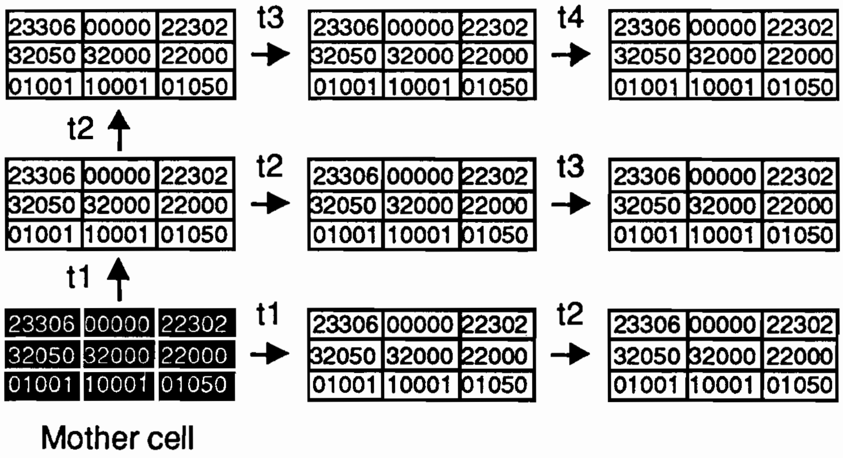


Fig. 3

These two cells will then be themselves copied into their own neighbors (time t2), and so on until the plan has been fully implemented. In the proposed example, the farthest cell is duplicated at time t4.

2. APPLICATION LEVEL: DESIGN METHODOLOGY

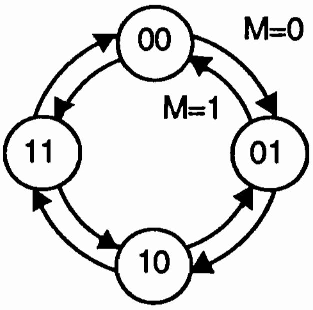
In order to illustrate the different steps of the design methodology, we have chosen a very simple example, a modulo-4 up-down counter. In a first step (§ 2.1), we will show that such a counter, like any other boolean function, can be represented by a binary decision diagram. In a second step (§ 2.2), we will suggest that this binary decision diagramcan be implemented at the application level by a new kind of field-programmable gate array (FPGA) satisfying the three basic characteristics discussed above: multi-cellular organization, cellular differentiation and cellular division.

2.1 Binary decision tree

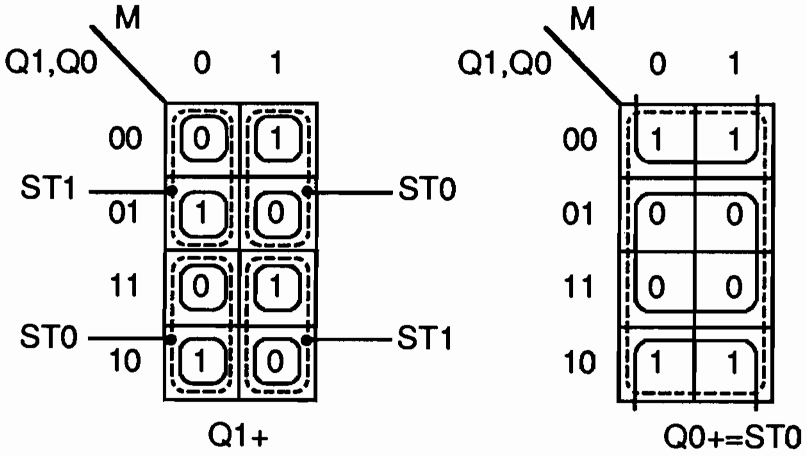
The counter is defined by the following sequences:

- for M = 0: Q1,Q0 = 00 -> 01 -> 10 -> 11 -> 00 (counting up);
- for M = 1: Q1,Q0 = 00 -> 11 -> 10 -> 01 -> 00 (counting down).

This definition is equivalent to the state graph of Fig. 4 and the two state tables of Fig. 5, defining the future states Q1+ and Q0+.These future states may be represented by *binary decision trees* (Fig. 6) in which each diamond is a *test element*, performing the test of an input variable, and each rectangle is an *output element* producing an output state (0 or 1).



Q1,Q0
Fig. 4



Q1,Q0 \ M	0	1
00	0	1
01	1	0
11	0	1
10	1	0

Q1+

Q1,Q0 \ M	0	1
00	1	1
01	0	0
11	0	0
10	1	1

Q0+=ST0

Fig. 5

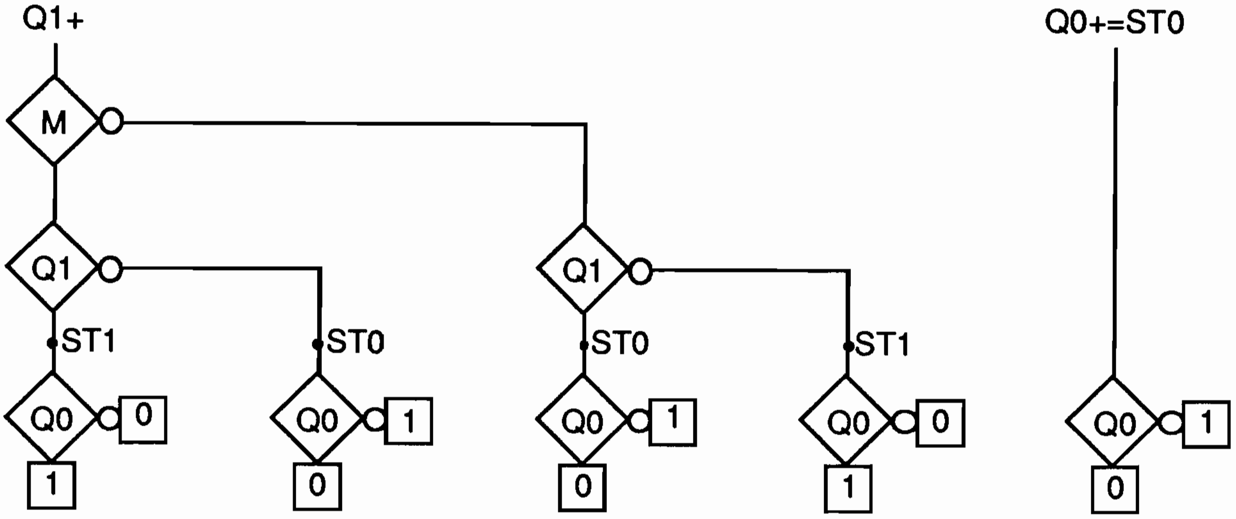


Fig. 6

It is well known that any boolean function can be represented by a binary decision tree; this mode of representation and the related methods are described for example in [Akers 78], [Bryant 92] and [Mange 92].

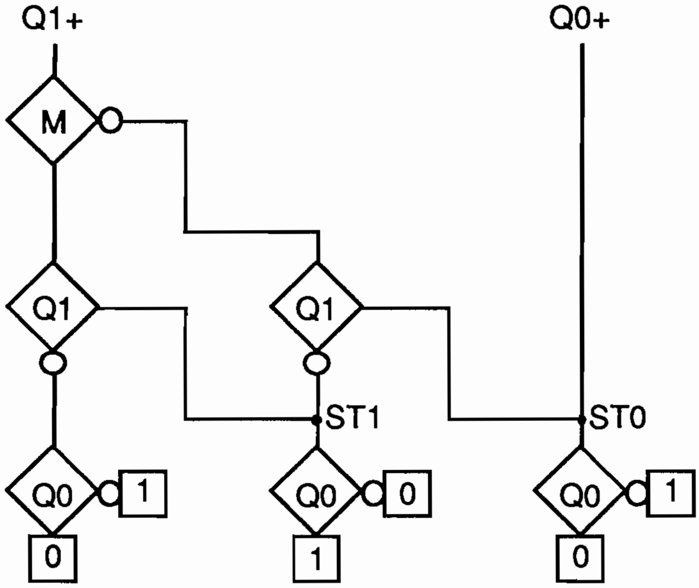


Fig. 7

We observe now that the trees in Fig. 6 can share two identical sub-trees (ST1 and ST0). This implies the convergence of branches of the trees and their transformation into the *normalized binary decision diagrams* of Fig. 7 which are characterized by the following constraints:

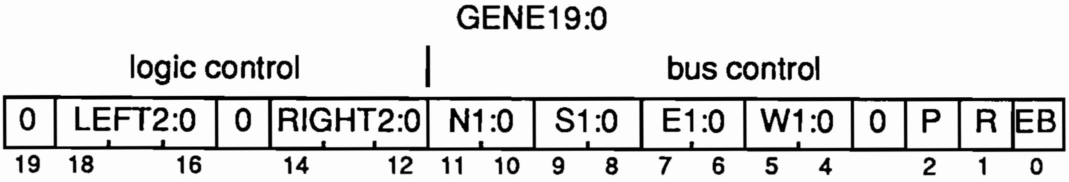
- each test element (diamond) is located on a rectangular array, at the intersection of a row and a column;
- each test element can only be connected to its nearest neighbours.

2.2 A new field-programmable gate array for multi-cellular organization

In order to implement in a piece of hardware any normalized binary decision diagram satisfying the general hypothesis of § 1.1 (2-dimensional homogeneous array of operators and connections) and the first characteristic of § 1.2 (multi-cellular organization), we have developed a prototype of a new field-programmable gate array based on a fine-grained cell built around a one variable multiplexer and called MUXTREE.

The detailed description of MUXTREE cell is beyond the scope of this paper and can be found in [Marchal 94]. It will be shown here how this array of multiplexers is programmed in order to calculate the gene of each cell and therefore to deduce the genome of the whole system.

We start from the definition of the 20 bits GENE19:0 (Fig. 8) that we have to program at the application level of each cell. These bits represent respectively the logic control and the bus control of the MUXTREE cell. The logic control is dedicated to the implementation the test elements and their local interconnections (Fig. 9). The bus control deals with the long connections and is mainly used to carry the input and output variables (Fig. 10).

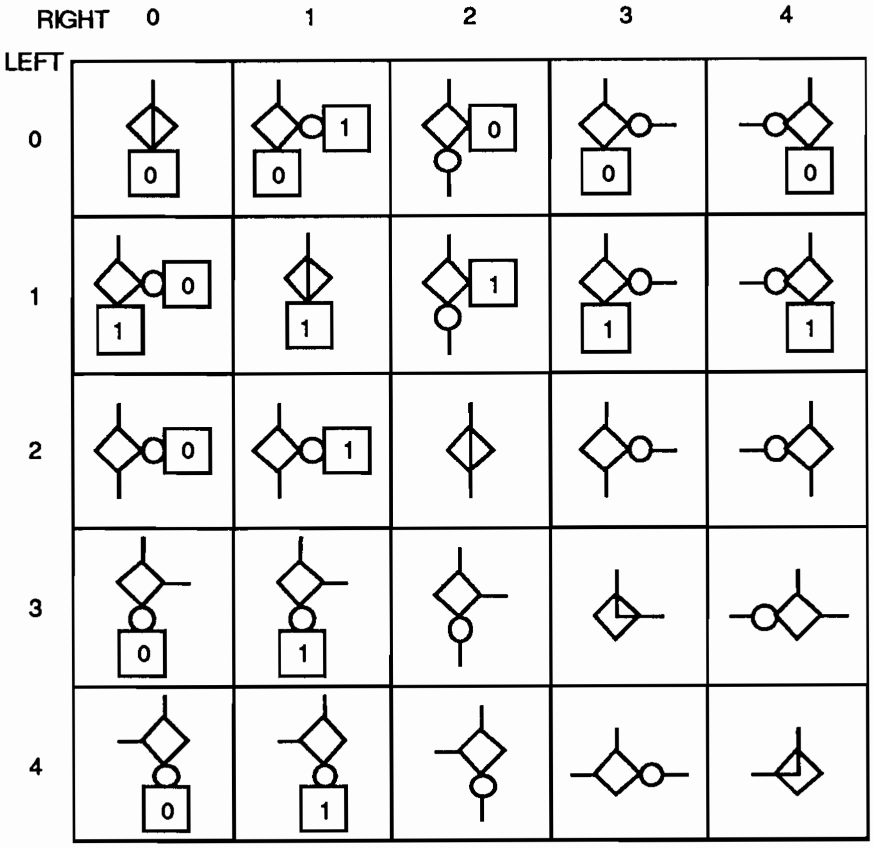


GENE19:0

logic control | bus control

0	LEFT2:0	0	RIGHT2:0	N1:0	S1:0	E1:0	W1:0	0	P	R	EB
19	18 16		14 12	11 10	9 8	7 6	5 4		2	1	0

Fig. 8


RIGHT
0
1
2
3
4
LEFT
0
1
2
3
4
0
0
1
0
0
0
0
0
1
0
1
1
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1
0
1
0
1

Fig. 9

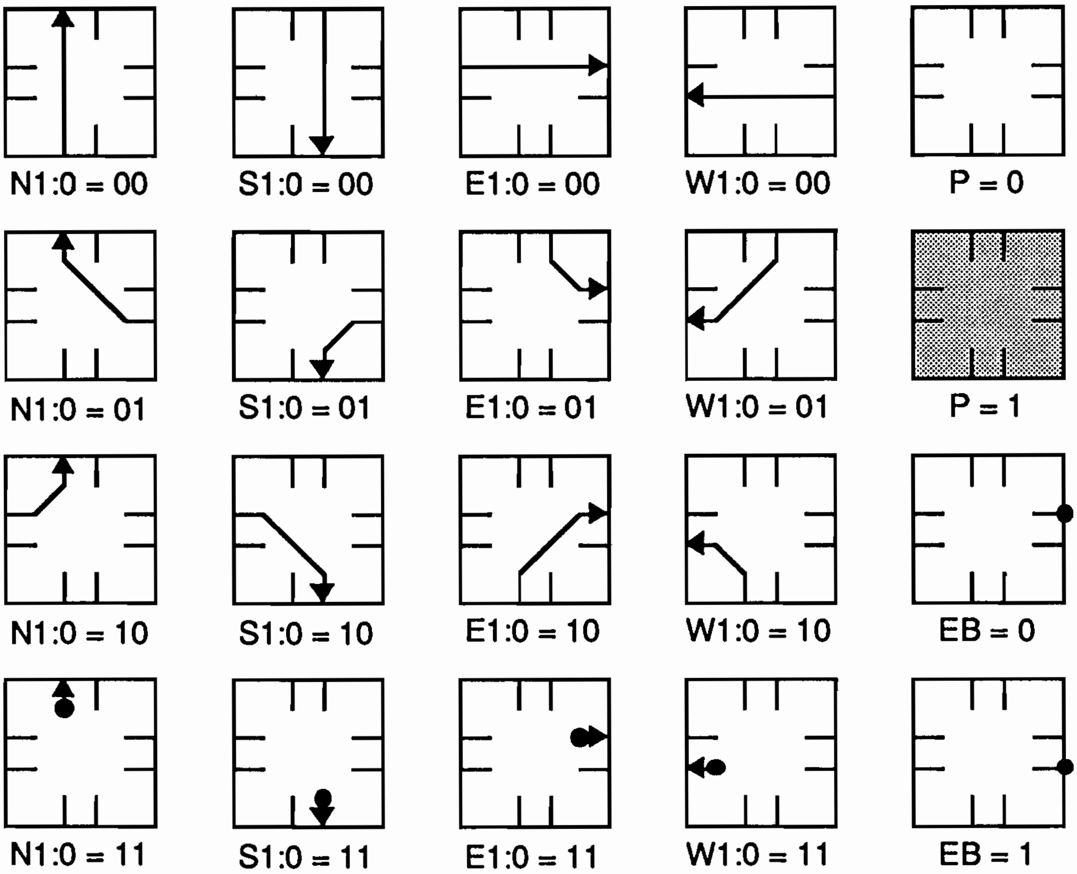
N1:0 = 00
S1:0 = 00
E1:0 = 00
W1:0 = 00
P = 0
N1:0 = 01
S1:0 = 01
E1:0 = 01
W1:0 = 01
P = 1
N1:0 = 10
S1:0 = 10
E1:0 = 10
W1:0 = 10
EB = 0
N1:0 = 11
S1:0 = 11
E1:0 = 11
W1:0 = 11
EB = 1

Fig. 10

We can now modify Fig. 7 in order to fit the logic control notation defined in Fig. 9 and generate the final diagram for the counter (Fig. 11), where the squares indicate that Q1 and Q0 are the registered values of Q1+ and Q0+. Using the bus control notation of Fig. 10, we draw then the connection layout of the counter (Fig. 12). In this layout the shadowed top lefthand side cell corresponds to P=1 and symbolizes its asynchronous initial preset. Combining the information of Fig. 11 and 12, according to the format defined in Fig. 8, produces the genome of Fig. 2.

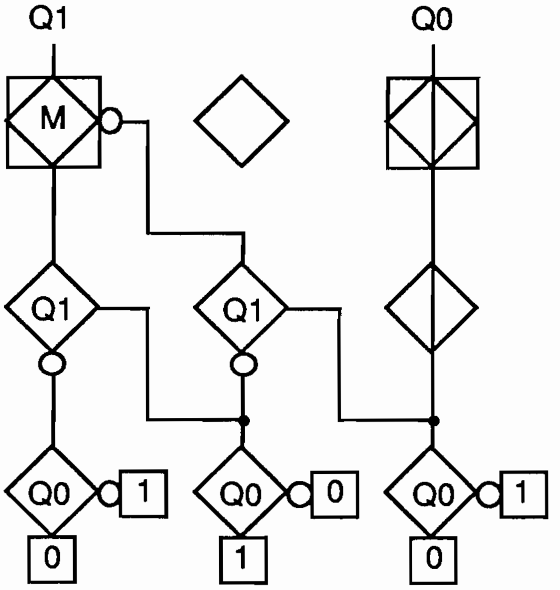

Fig. 11

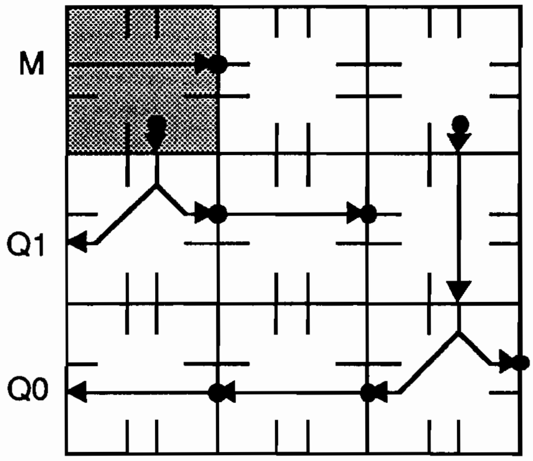

Fig. 12

3. CONFIGURATION LEVEL: BIOLOGICAL-LIKE PROPERTIES

The second characteristic of § 1.2 (cellular differentiation) necessitates a copy of the whole genome in each cell's RAM (Fig. 2), together with the right coordinates at the right place. This is done at the configuration level where:

- each cell of the MUXTREE array is equipped with a RAM;
- each RAM is addressed by a word x,y, where x is the horizontal coordinate and y the vertical coordinate; the calculation of the coordinates x and y is realized by simple incrementation.

For normal operation of our counter, a rectangular array of 3 columns and 3 rows, i.e. 9 MUXTREE cells is sufficient. More cells are necessary in case of self-repairing or self-reproduction processes.

3.1 Self-reproduction mode

Duplicating a given function is staightforward. Suppose we have three spare columns. With the original border condition (x=1 as in Fig. 13) and assuming a boolean horizontal coordinate x, the chain of modulo-3 incrementers will produce the following values for the horizontal coordinate x, read from left to right: 1, 2, 3, 1, 2, 3. Combined with the vertical coordinate y which is unchanged, the pattern of the horizontal coordinate x produces two copies of the original array of Fig. 1 and, therefore, two copies of the same counter.

3.2 Self-repair mode

Suppose we have a faulty cell in the second column of the counter (Fig. 14) and we have at our disposal one spare column at the right of the array. A built-in self-test (BIST) configuration of the cellular array, as described in [Abramovici 95], allows us to detect such a fault. It is then possible to reconfigure the array with the original genome and define a new counter by short-cutting the incrementers of the faulty column. Thus replacing x=3 by x=2 results in a shift of the two righthand side columns one column to the right (thanks to the chain of modulo-3 incrementers) and allows us to obtain the new and correct version of the counter.

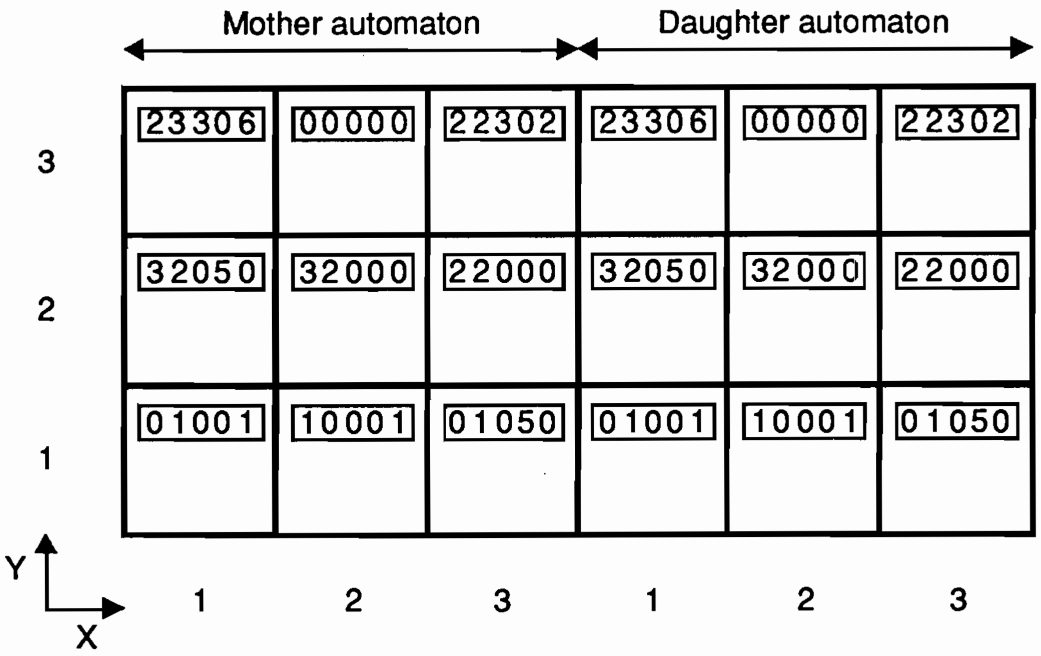

Fig. 13

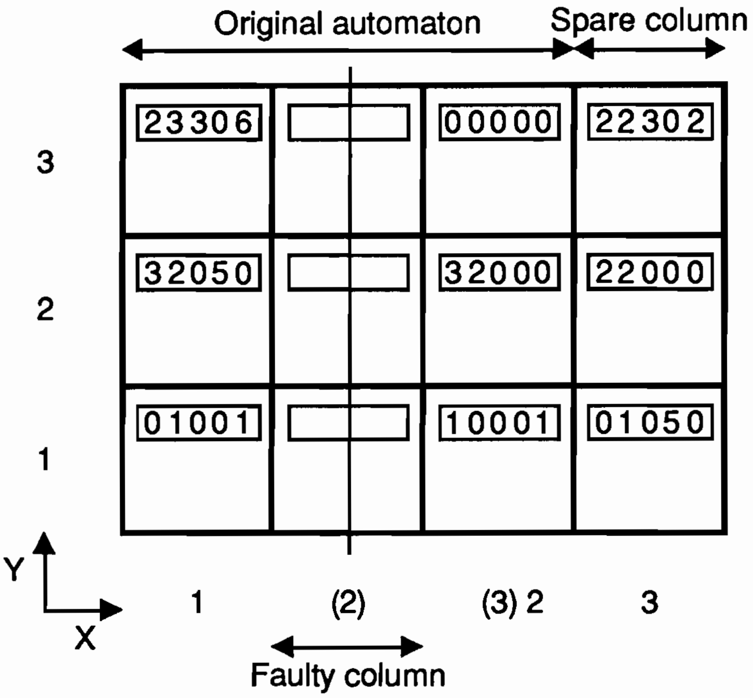

Fig. 14

3. CONCLUSION

A MUXTREE cell array defines a sea-of-gates type FPGA where binary decision diagrams are directly implemented at the application level. Using this circuit, the design methodology starts therefore with the minimization of binary decision diagrams on a rectangular array. The mapping of the test elements and local connections of such diagrams is then operated straightforward into the cell array. The biological-like properties, which preserve this mapping, become consequently trivial procedures. They rely upon the circuit reconfiguration capabilities provided by the configuration level.

Among the biological-like proprieties, the interest of self-repair is immediately obvious, as this property allows the repair of isolated faults, for example, the fault of a single cell. The importance of self-reproduction is less evident, and can be justified by:

- the complete reconstruction of a device, in case of massive faults;
- the automatic realization of homogeneous 2-dimensional cellular automata, by repetition of the same basic cell;
- the simplicity of moving a device in the cellular array by the simple alteration of the coordinates of the parent cell.

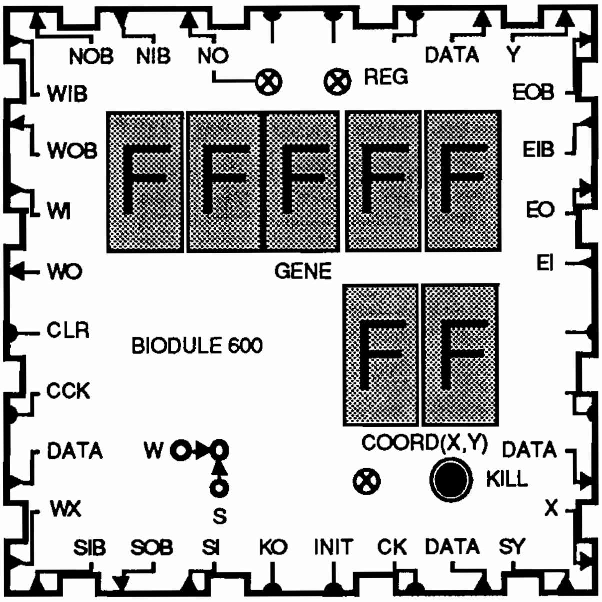

Fig. 15

Using standard FPGA and RAM circuits, we have implemented a first prototype of our MUXTREE cell (Fig. 15), which we have called "Biodule" [Durand 94]. With a couple of these biodules, we have successfully verified the self-reproduction and self-repair processes illustrated in Fig. 13 and 14.

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