Biomorphs Implemented as a Data and Signals Cellular Automaton

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Abstract. Traditionally the cell of an automaton implements the rule table defining the state of the cell at the next time step knowing its present state and those of its neighbors. The cell deals consequently only with states. The novel cell involved here handles data and signals. It is designed as a digital system made up of a processing unit and a control unit. It allows the realization of growing structures like Biomorphs. The hardware implementation of these Biomorphs takes place in our electronic wall for bio-inspired applications, the *BioWall*.

1 Introduction: Cellular Automata

Cellular automata were originally conceived by S. M. Ulam and J. von Neumann in the 1940s to provide a formal framework for investigating the behavior of complex, extended systems. They are part of the early history of self-replicating machines and of von Neumann's thinking on the matter [1],[2]. Nowadays, they still remain the framework of less complex replicating structures: the self-replicating loops.

One of the central models used to study self-replication is that of cellular automata. These automata are dynamical systems in which space and time are discrete. A cellular automaton (CA) consists of an array of cells, each of which can be in one of a finite number of possible states, updated synchronously in discrete time steps, according to a local interaction rule. The state of a cell at the next time step is determined by the current states of a surrounding neighborhood of cells. This transition is usually specified in the form of a rule table, delineating the cell's next state for each possible neighborhood configuration. The cellular array (grid) is n-dimensional, where $n = 1, 2, 3$ is used in practice [3], [4].

Fig. 1a shows the basic automaton cell AC defined in a two-dimensional, nine-neighbor cellular space. This cell receives the states NSI, $NESI$, ESI, $SESI$, SSI, $SWSI$, WSI, and $NWSI$ from the cells to the south, southwest, west, northwest, north, northeast, east, and southeast respectively. The cell also shares its own state SO directly or indirectly with its eight neighbors. Such a cell deals consequently only with input and output states. Its implementation is a sequential machine resulting from the interconnection of the rule table TAB

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and the state register REG (Fig. 1b). In order to simplify the design of the cell, the register REG is sometimes functionally sliced into multiple state variable groups called fields. The utilization of such fields also makes the resulting rules of the table TAB much more readable.

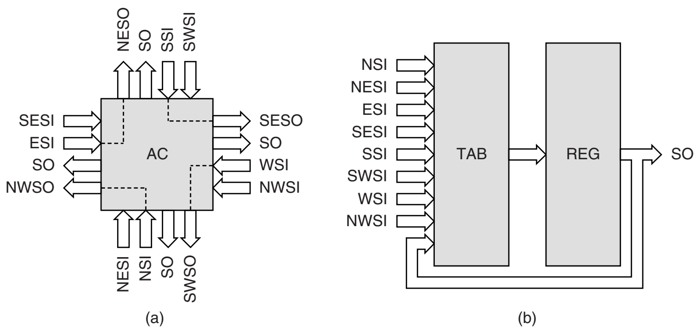


Fig. 1. Two-dimension, nine-neighbor CA. (a) Basic cell. (b) Rule table TAB and state register REG.

This paper involves a novel cellular automaton processing both data and signals. Such an automaton, whose basic cell corresponds to a digital system, is well adapted to the realization of growing structures. Section 3 introduces such growing structures: the Biomorphs. The design of the corresponding automaton cell and its hardware implementation are discussed in Section 4 and Section 5 respectively. Finally, we present concluding remarks in Section 6.

2 Data and Signals Cellular Automaton

The basic cell of our novel automaton, the data and signals cellular automaton (DSCA), works with northward (N), northeastward (NE), eastward (E), southeastward (SE), southward (S), southwestward (SW), westward (W), and northwestward (NW) directed data (D) and signals (S) (Fig. 2a). The cell computes their digital outputs O from their digital inputs I. In opposition to the state shared by the traditional cell (Fig. 1), these data and signals outputs are not necessarily identical for all the neighboring cells.

Each cell of the automaton is designed as a digital system resulting from the interconnection of a data processing unit PU and a control unit CU (Fig. 2b). In this digital system, the processing unit handles the data. It is made up of input selectors SEL, data registers REG, and output buffers BUF (Fig. 3a). The control unit of the digital system computes the signals. It combines input encoders ENC, control registers REG, and output generators GEN (Fig. 3b).

3 Biomorphs

The word *Biomorph* was devised by surrealist artist D. Morris to describe animal-like shapes in his work [5]. In the Artificial Life tradition, R. Dawkins designed a computer program to explore how complex patterns can arise from simple rules [6]. His main goal was to abstract and reduce to a minimum the amount of hand-design in order to build the Biomorphs. Simple growing rules (embryology) and guided evolution would ideally produce biologically interesting results.

In opposition to the Biomorphs defined in the literature, which implement also mutation and evolution through a combination of automatic and human-guided selection, our creatures only express a sequence of genes in order to increase. They are implemented as growing structures involving the component and data informations shown in Fig. 4.

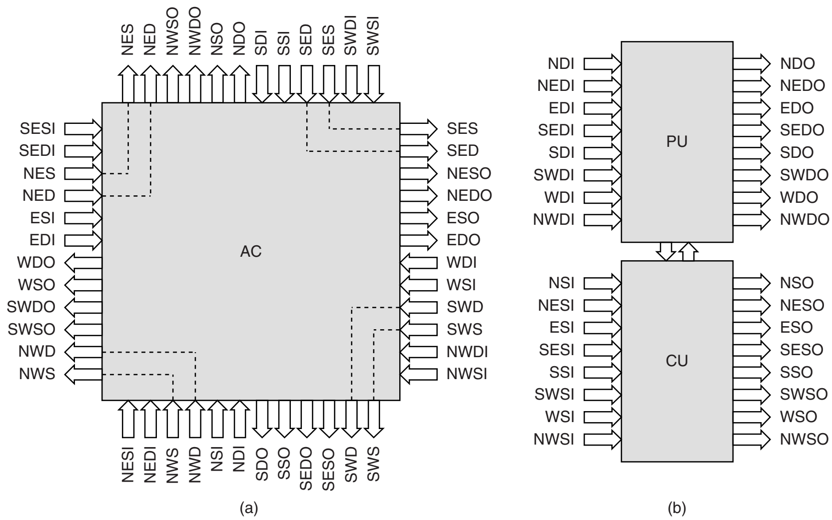


Fig. 2. Two-dimension, nine-neighbor DSCA. (a) Basic cell. (b) Processing unit PU and control unit CU.

Without any external solicitation, the central component of the initial Biomorph (Fig. 5a) presents only empty data and its structure remains unchanged (time step 0). When a physical input is provided, a gene G appears first (time step 1), propagates then along the members (time step 2), and finally expresses itself in the apex components (time step 3). Depending on the number L of apex components of its initial structure (Fig. 5b), the Biomorph will develop a creature having four, six, or eight legs.

When activated the central component produces a gene G whose value is comprised between 0 and 7. Fig. 6a shows the expression of these eight genes

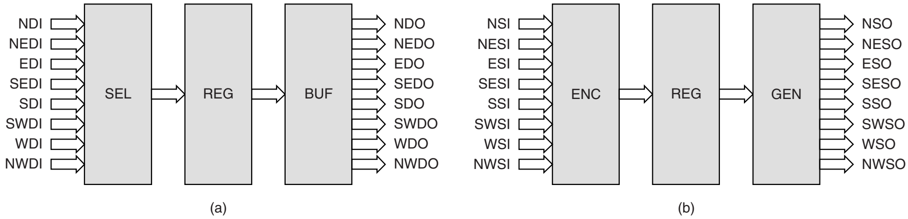


Fig. 3. Detailed architecture of the DSCA cell. (a) Processing unit. (b) Control unit.

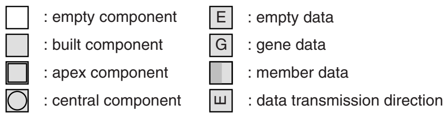


Fig. 4. Component and data informations of the Biomorphs.

for each of the eight members of the Biomorph. Starting with four-legged, six-legged, and eight-legged initial Biomorphs and applying these expressions to a sequence of four genes $G = 1, 1, 2, 2$ leads to the growth developments of Fig. 6b.

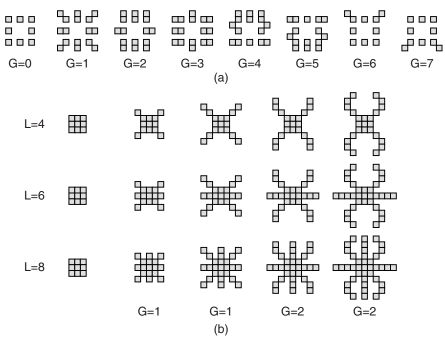


Fig. 5. Biomorph. (a) Three-time-step growth cycle. (b) Four-legged, six-legged, and eight-legged creature.

4 Cell Design

The cell is a digital system whose processing unit assures the propagation of the data and whose control unit produces the signals implied in the growth of the Biomorph. In addition to the data propagation, the digital system must perform the gene expression represented in Fig. 7. The resources needed in order to do it define the architecture of the cell (Fig. 8a). The processing unit involves the following ones:

– A 3-bit data register G2:0 for the memorization of the gene (000=empty, 001=straight growth, 010=curved in, 011=curved out, 100=curved up, 101=curved down, 110=top growth, 111=bottom growth).
– A 3-bit data register M2:0 for the memorization of the member (000=north, 001=northeast, 010=east, 011=southeast, 100=south, 101=southwest, 110=west, 111=northwest).
– A 8-input multiplexer DIMUX for the selection of one of the eight input data $NDI2:0$, $NEDI2:0$, $EDI2:0$, $SEDI2:0$, $SDI2:0$, $SWDI2:0$, $WDI2:0$ or $NWDI2:0$.
– A 2-input multiplexer DOMUX for the selection of the gene or the member as output data $DO2:0$.

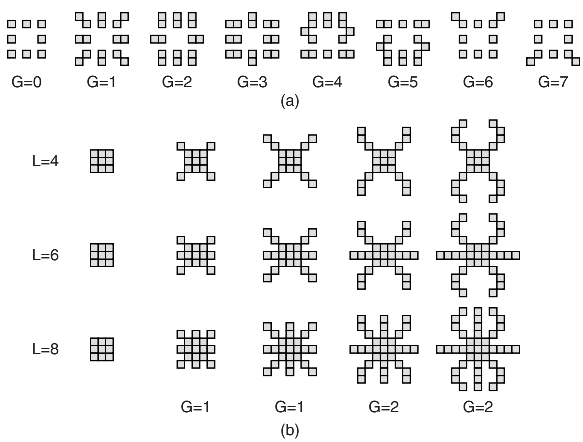


Fig. 6. Genes 0 to 7. (a) Expression for all the members of the Biomorph. (b) Developments resulting from the sequence $G = 1, 1, 2, 2$.

The control unit consists of six resources:

– A 3-bit transmission register T2:0 for the memorization of the input selection (000=northward, 001=northeastward, 010=eastward, 011=southeastward, 100=southward, 101=southwestward, 110=westward, 111=northwestward).
– A 1-bit control register B to indicate whether the component is empty ($B = 0$) or built ($B = 1$).
– A 1-bit apex register A to point out each extremity of the growing structure ($A = 1$) and perform the selection of its gene ($A = 0$) or its member ($A = 1$) as output data.

– A 1-bit control register C to define the central component of the Biomorph ($C = 1$).
– An input signals SI encoder ENC.
– An output signals SO generator GEN.

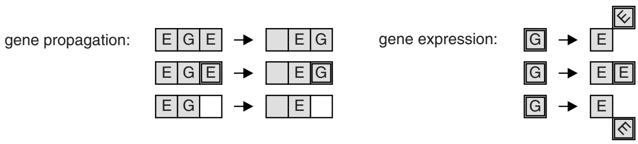
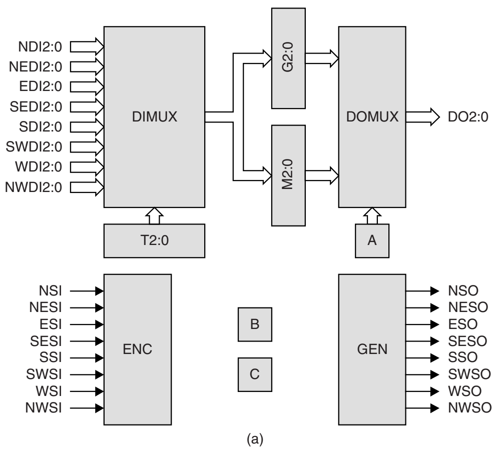


Fig. 7. Propagation and expression operations involved in the growth process.



operation	description	B	A	VSI	VSO
idle cell	G <= 000	0	-	0	-
member growth	B <= 1 A <= 1 G <= 000 M <= BDI T <= TCI	0	-	1	-
gene propagation	G <= BDI	1	0	-	-
idle apex	G <= BDI	1	1	-	0
gene expression	A <= 0 G <= BDI	1	1	-	1

(b)

Fig. 8. Biomorph cell. (a) Detailed architecture. (b) Operation table.

The control variables B and A as well as the valid signal input VSI and the valid signal output VSO define the operations performed by the data and control registers (Fig. 8b). While the variables B and A proceed directly from the corresponding control registers, the input encoder ENC computes VSI and VSO according to the following equations:

$$VSI = NSI + NESI + ESI + SESI + SSI + SWSI + WSI + NWSI \quad (1)$$

$$VSO = NSO + NESO + ESO + SESO + SSO + SWSO + WSO + NWSO \quad (2)$$

In the operation table (Fig. 8b), the biomorph data information $BDI2:0$ results from the selection operated by the input multiplexer DIMUX according to its control variables $SEL2:0$:

$$SEL2 = B'.TCI2 + B.T2 \quad (3)$$
$$SEL1 = B'.TCI1 + B.T1 \quad (4)$$
$$SEL0 = B'.TCI0 + B.T0 \quad (5)$$

The transmission control information $TCI2:0$ involved in these relations realizes a priority encoding of the input signals SI:

$$TCI2 = NSI'.NESI'.ESI'.SESI'.(SSI + SWSI + WSI + NWSI) \quad (6)$$
$$TCI1 = NSI'.NESI'.(ESI + SESI) + NSI'.NESI'.ESI'.SESI'.(WSI + NWSI) \quad (7)$$
$$TCI0 = NSI'.NESI \quad (8)$$

The generator GEN implements the output signals SO involved in the gene propagation and gene expression operations of the growth process (Fig. 7). The computation of these signals is based on eight memories MEM0 to MEM7, each of them defining a given signal for all the genes, members and transmission directions of the Biomorph cell:

$$NSO = C'.B.A.MEM0(G, M, T) + C.EIN \quad (9)$$
$$NESO = C'.B.A.MEM1(G, M, T) + C.EIN \quad (10)$$
$$ESO = C'.B.A.MEM2(G, M, T) + C.EIN \quad (11)$$
$$SESO = C'.B.A.MEM3(G, M, T) + C.EIN \quad (12)$$
$$SSO = C'.B.A.MEM4(G, M, T) + C.EIN \quad (13)$$
$$SWSO = C'.B.A.MEM5(G, M, T) + C.EIN \quad (14)$$
$$WSO = C'.B.A.MEM6(G, M, T) + C.EIN \quad (15)$$
$$NWSO = C'.B.A.MEM7(G, M, T) + C.EIN \quad (16)$$

According to these equations, the central component ($C = 1$) delivers an output signal to all the neighboring cells whenever the external input EIN is activated. Simultaneously, the central component produces also a random gene on its output data $DO2:0$.

5 Hardware Implementation

The hardware implementation of the nine-neighbor DSCA takes place in our two-dimensional electronic wall for bio-inspired applications, the *BioWall* (Fig. 9) [7]. In the implementation of the Biomorphs, each cell of the automaton corresponds to a unit in the wall. This unit is the combination of three elements: (1) an input device, (2) a digital circuit, and (3) an output display.

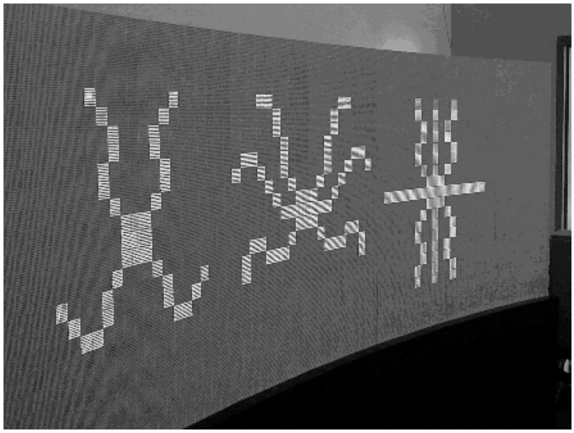


Fig. 9. The BioWall used to physically implement the Biomorphs (Photograph by A. Badertscher).

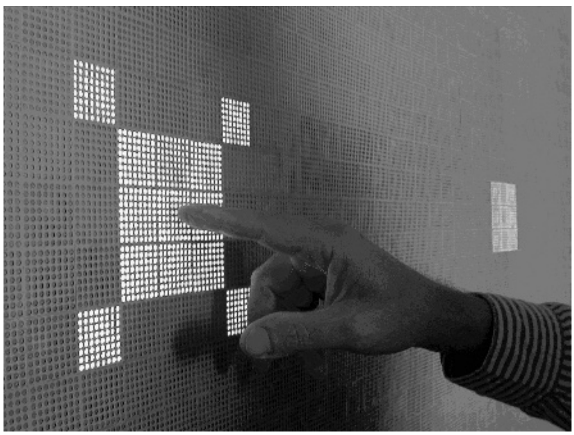


Fig. 10. Touching the central cell to physically activate the growth of the Biomorph (Photograph by A. Badertscher).

The unit's outer surface consists of a touch-sensitive panel which acts like a digital switch. This switch enables the user to click on the central cell of the Biomorph and generate a gene in order to activate the growth of its members (Fig. 10).

The unit's internal digital circuit is a field-programmable gate array (FPGA), configured so as to implement: (1) external (touch) input, (2) execution of the propagation and expression operations involved in the growth process, and (3) control of the output display. This latter is a two color light-emitting diode

(LED) display, made up of 128 diodes arranged as an 8×8 dot-matrix, each dot containing a green and a red LED. The display allows the user to view the cell's current data and to choose the gene generated by the central component.

6 Concluding Remarks

We presented a novel cellular automaton dealing with data and signals instead of states. Even though this automaton is specially well suited for the realization of growing structures, it constitutes a general model for all kind of cellular applications. It allows and simplifies in fact the design of all the cells where a great number of states leads to an explosion of the rule table.

The Biomorphs are growing structures whose complex behavior leads to the design of a data and signals automaton instead of a state based one. The data processing unit and the control unit of its basic cell introduces the characteristic resources and registers of all digital sytems. The hardware implementation of the Biomorphs takes place in the BioWall, our electronic wall for bio-inspired applications.

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