Data and Signals: A New Kind of Cellular Automaton for Growing Systems

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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 consequently processes only with states. The novel cell presented here handles data and signals. It is designed as a digital system made up of a processing unit and a control unit. The realization of interactive self-replicating loops will serve as an application example of growing systems. The hardware implementation of these loops takes place in our electronic wall for bio-inspired applications, the BioWall.

1 Introduction: Cellular Automata

Cellular automata were originally conceived by Ulam and 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]. 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 [2], [3].

Fig. 1 shows the basic automaton cell, AC, defined in a two-dimensional, five-neighbor cellular space. This cell receives the states ES, NS, WS, and SS from the cells to the west, south, east, and north respectively. The cell also shares its own state S with its four neighbors. Such a cell consequently processes only input and output states. Its implementation is a sequential machine resulting from the interconnection of the rule table TAB and the state register REG (Fig. 2). 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 makes also the resulting rules of the table TAB much more readable.

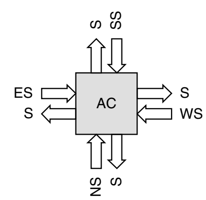

Figure 1. The basic cell of a two-dimension, five-neighbor CA.

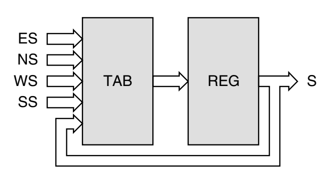

Figure 2. The rule table TAB and the state register REG of the automaton cell.

In this paper we present a novel cellular automaton processing both data and signals. Such an automaton, whose basic cell corresponds to a digital system, is well adapted

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to the realization of growing structures. Section 3 introduces the interactive self-replication loops as an application example. 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 eastward (E), northward (N), westward (W), and southward (S) directed data (D) and signals (S) (Fig. 3). 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.

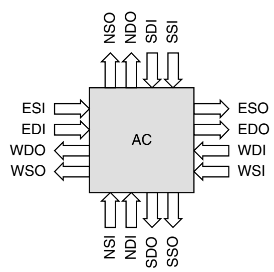

Figure 3. The basic cell of the novel two-dimensional, five-neighbor DSCA.

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. 4). In this digital system, the processing unit processes the data. It is made up of input selectors, SEL, data registers REG, and output buffers BUF (Fig. 5). The control unit of the digital system handles the signals. It combines input encoders ENC, control registers REG, and output generators GEN (Fig. 6).

3 Application: Interactive Self-Replicating Loops

The first self-replicating CA was devised by Langton in 1984 [4]. This was a configuration in the form of a loop, endowed with a constructing arm and replication information. After 151 time steps, the original loop (mother loop) produced a daughter loop, thus fulfilling self-replication. This 8×8 loop was implemented with a sheath around it. Later, Byl [5] proposed a simplified version of Langton's automaton. More recently, Reggia *et al.* [6] discovered that having

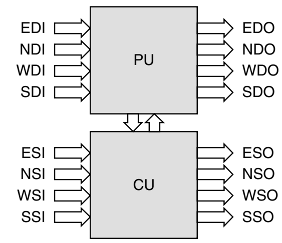

Figure 4. The processing unit PU and the control unit CU of the automaton cell.

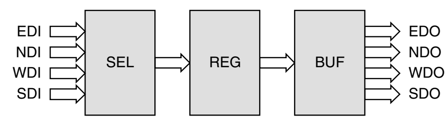

Figure 5. The detailed architecture of the processing unit.

a sheath surrounding the loop was not essential, and that its removal led to smaller self-replicating structures.

As opposed to the loops defined in the literature which perform self-replication continually, the loops designed bellow are idle unless physically activated [7]. These unsheathed $n \times n$ loops, with $n \geq 2$, correspond therefore to interactive self-replicating loops [8]. They are implemented as growing systems involving the component, apex, and data informations shown in Fig. 7.

With no external trigger, the minimal 2×2 loop remains idle producing continually the same four-time-step cycle of Fig. 8. In the same way, as long as no physical input is provided, the 3×3 loop is inert, continually undergoing an eight-time-step cycle (Fig. 9).

When activated the idle loop self-replicates. Depending on the initially activated cell, the self-replication process can occur in all of the four cardinal directions. Fig. 10 and Fig. 11 show the self-replication process performed eastward for the 2×2 and the 3×3 loop respectively. This process is performed within 24 time steps for the first loop

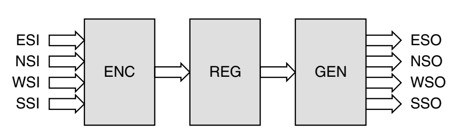

Figure 6. The detailed architecture of the control unit.

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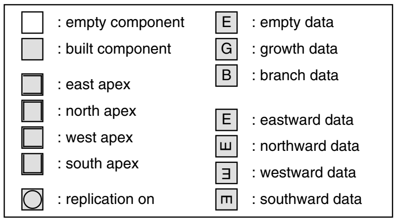

Figure 7. Component, apex, and data states of the loops.

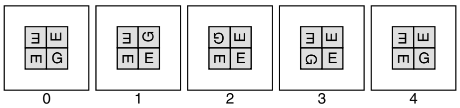

Figure 8. The four-time-step idle cycle of the minimal 2×2 loop.

and 48 for the second one.

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 and cleavage of the self-replicated loop. In addition to the data propagation, the digital system must perform the operations represented in Fig. 12. The resources needed in order to do it define the architecture of the cell (Fig. 13). The processing unit involves the following ones:

- A 2-bit data register D1:0 for the memorization of the output data $DO1 : 0$ (empty=00, growth=01, branch=10).

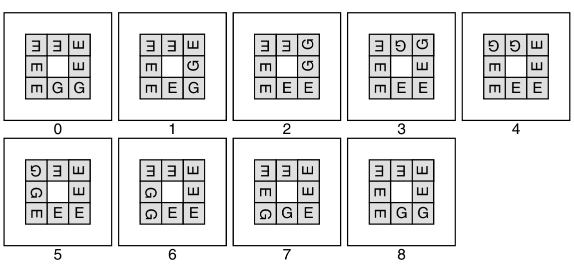

Figure 9. The eight-time-step idle cycle of the 3×3 loop.

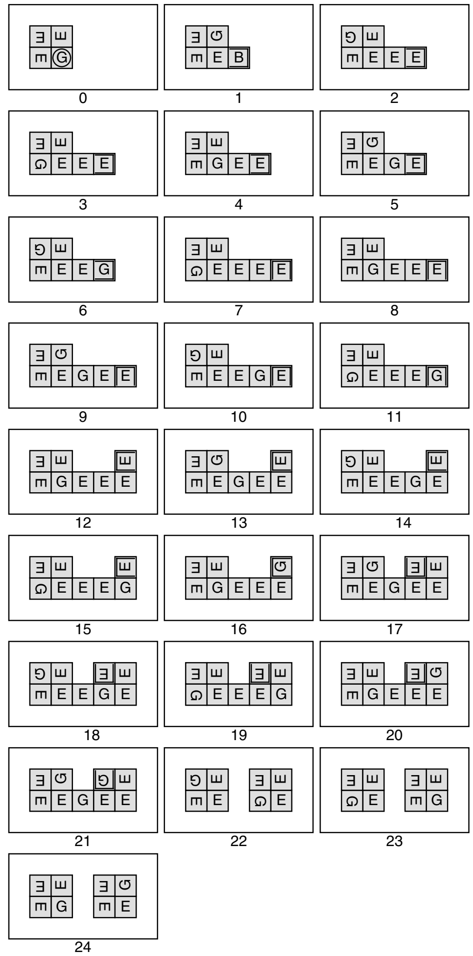

Figure 10. The eastward directed self-replication process of the 2×2 loop.

- A 4-input multiplexer MUX for the selection of one of the four input data lines, $EDI1 : 0$, $NDI1 : 0$, $WDI1 : 0$, or $SDI1 : 0$.

The control unit consists of six resources:

- A 2-bit transmission register T1:0 for the memorization of the input selection (eastward=00, northward=01, westward=10, southward=11).
- A 1-bit control register B to indicate whether the component is empty ($B = 0$) or built ($B = 1$).
- A 3-bit apex register A2:0 to point out the extremity and orientation of the growing structure (empty=0XX, east=100, north=101, west=110, south=111).

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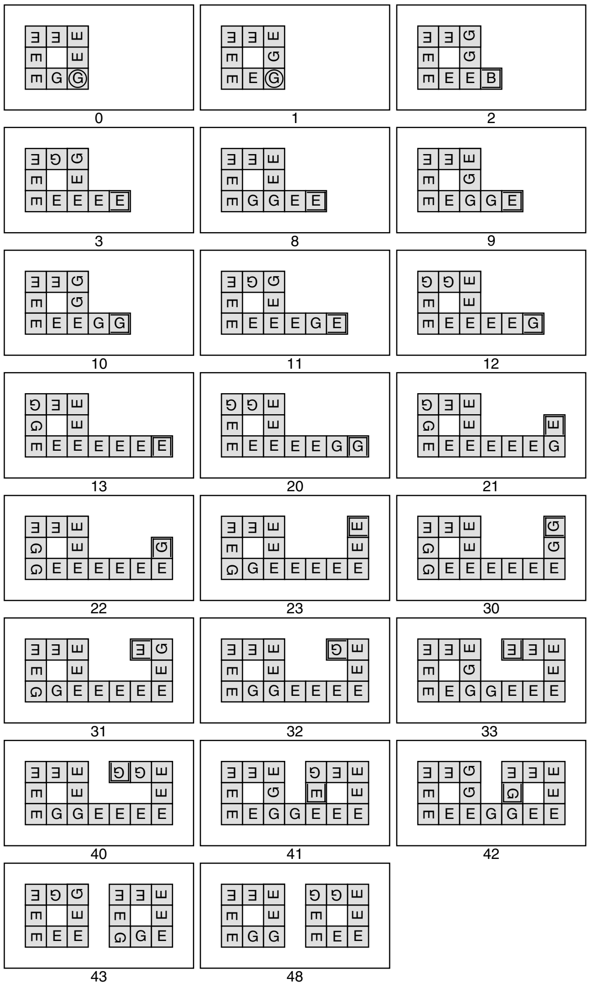

Figure 11. The eastward directed self-replication process of the 3×3 loop.

- A 1-bit replication register R to memorize the activation of the cell (off=0, on=1).
- An input signals $SI2:0$ encoder ENC.
- An output signals $SO2 : 0$ generator GEN (empty=0XX, branching growth=100, linear growth=101, turning growth=110, cut-off=111).

The control variable B and the branch signal input BSI define the operations performed by the data register D1:0 (Fig. 14). While the variable B proceeds directly from the corresponding control register, the input encoder ENC computes the signal BSI according to the following equation:

$$\begin{aligned} BSI &= ESI2.ESI1'.ESI0' \\ &+ NSI2.NSI1'.NSI0' \\ &+ WSI2.WSI1'.WSI0' \\ &+ SSI2.SSI1'.SSI0' \end{aligned} \tag{1}$$

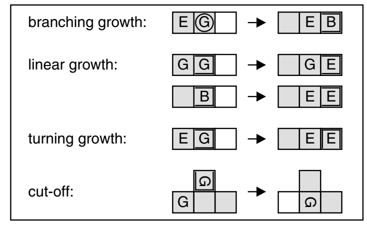

Figure 12. The growth and cleavage operations involved in the self-replication process.

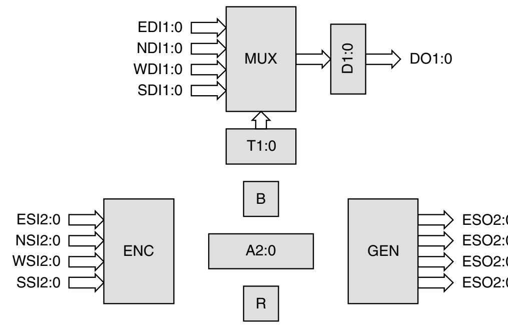

Figure 13. Detailed architecture of the self-replicating loop cell.

In the operation table, the loop data information $LDI1:0$ is selected by the 4-input multiplexer MUX.

operation	description	B	BSI
HOLD	D <= D	0	0
LOAD	D <= LDI	1	-
BRANCH	D <= 10	0	1

Figure 14. Operation table of the data register D1:0.

The encoder also generates the growth signal input GSI and the cut-off signal input CSI in order to activate the operations executed by the control register B (Fig. 15). These signals verify the relations:

$$\begin{aligned} GSI &= ESI2.ESI1' + NSI2.NSI1' \\ &+ WSI2.WSI1' + SSI2.SSI1' \\ &+ ESI2.ESI0' + NSI2.NSI0' \end{aligned}$$

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$$
\begin{aligned}
& + \quad WSI2.WSI0' + SSI2.SSI0' && (2)\\
CSI &= ESI2.ESI1.ESI0 \\
& + \quad NSI2.NSI1.NSI0 \\
& + \quad WSI2.WSI1.WSI0 \\
& + \quad SSI2.SSI1.SSI0 && (3)
\end{aligned}
$$

operation	description	GSI	CSI
HOLD	B <= B	0	0
SET	B <= 1	1	-
RESET	B <= 0	0	1

Figure 15. Operation table of the control register B.

In Fig. 16, the loading of the transmission control information:

$$TCI1 = WSI2 + SSI2 \quad (4)$$

$$TCI0 = NSI2 + SSI2 \quad (5)$$

depends on a valid signal input:

$$VSI = ESI2 + NSI2 + WSI2 + SSI2 \quad (6)$$

operation	description	VSI
HOLD	T <= T	0
LOAD	T <= TCI	1

Figure 16. Operation table of the transmission register T1:0.

In addition to the control variable B, the apex signal input ASI and the valid signal output VSO given hereafter:

$$ASI = BSI + GSI \quad (7)$$

$$VSO = ESO2 + NSO2 + WSO2 + SSO2 \quad (8)$$

activate the operations of the apex register A2:0 (Fig. 17). The apex control information:

$$ACI2 = 1 \quad (9)$$

$$ACI1 = WGSI + SGSI \quad (10)$$

$$ACI0 = NGSI + SGSI \quad (11)$$

results from the encoder. These equations include the north, west and south growth signal inputs:

$$
\begin{aligned}
NGSI &= NSI2.NSI1' \\
& + \quad ESI2.ESI1.ESI0' && (12)\\
WGSI &= WSI2.WSI1'
\end{aligned}
$$

operation	description	B	ASI	VSO
HOLD	A <= A	-	0	0
		1	-	0
LOAD	A <= ACI	0	1	0
RESET	A <= 000	-	-	1

Figure 17. Operation table of the apex register A2:0.

$$
\begin{aligned}
& + \quad NSI2.NSI1.NSI0' && (13)\\
SGSI &= SSI2.SSI1' \\
& + \quad WSI2.WSI1.WSI0' && (14)
\end{aligned}
$$

The operations of the replication register R (Fig. 18) implies the external input EIN (activated by pressing the corresponding touch-sensitive switch of the BioWall) and the branch signal output BSO:

$$
\begin{aligned}
BSO &= ESO2.ESO1'.ESO0' \\
& + \quad NSO2.NSO1'.NSO0' \\
& + \quad WSO2.WSO1'.WSO0' \\
& + \quad SSO2.SSO1'.SSO0' && (15)
\end{aligned}
$$

operation	description	EIN	BSO
HOLD	R <= R	0	0
SET	R <= 1	1	-
RESET	R <= 0	0	1

Figure 18. Operation table of the replication register R.

The generator GEN implements the output signals involved in the growth and cleavage operations of the self-replication process (Fig. 12). The computation of the eastward signals $ESO2:0$ is based on the definition of the corresponding east branching growth EBG, east linear growth ELG, east turning growth ETG and east cut-off ECO variables:

$$ESO2 = B.(EBG + ELG + ETG + ECO) \quad (16)$$

$$ESO1 = B.(ETG + ECO) \quad (17)$$

$$ESO0 = B.(ELG + ECO) \quad (18)$$

These east variables depend on the data and control informations of the cell:

$$EBG = (D1'.D0).(LDI1'.LDI0').(T1'.T0').R \quad (19)$$

$$
\begin{aligned}
ELG &= (D1'.D0).(LDI1'.LDI0).(A2.A1'.A0') \\
& + \quad (D1.D0').(A2.A1'.A0') && (20)\\
ETG &= (D1'.D0).(LDI1'.LDI0').(A2.A1'.A0')
\end{aligned}
$$

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$$ \tag{21} $$

$$ECO = (T1.T0').NSI2 \tag{22}$$

The northward $NSO2:0$, westward $WSO2:0$ and southward $SSO2:0$ signals are computed in a similar way.

5 Hardware Implementation

The hardware implementation of the five-neighbor DSCA takes place in our two-dimensional electronic wall for bio-inspired applications, the $BioWall$ (Fig. 19) [9]. In the implementation of the loops, 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.

Figure 19. The BioWall used to physically implement the loops (Photograph by A. Badertscher).

The unit's outer surface consists of a touch-sensitive panel which acts like a digital switch, enabling the user to click on the cell and thereby activate self-replication (Fig. 20).

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 growth and cleavage operations involved in the loop replication 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 whether it is in an activated or deactivated mode.

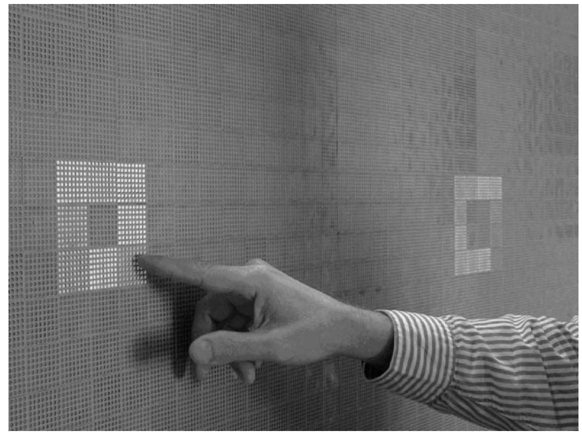

Figure 20. Touching a cell to physically activate the loop (Photograph by A. Badertscher).

6 Concluding Remarks

We presented a novel cellular automaton processing 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 interactive self-replication loops are introduced as an easy understandable example of growing system. The design of the data processing unit and the control unit of the corresponding automaton cell introduces the characteristic resources and registers of all digital sytems. This digital system based cell is entirely generic, allowing the realization of all $n \times n$ loops with $n \geq 2$, in opposition to the former sequential machine based ones [7], [8], where distinct rule tables are needed depending on the loop size. The hardware implementation of the loops takes place in the BioWall, our electronic wall for bio-inspired applications.

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