Embryonic Machines that Grow, Self-Replicate and Self-Repair

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Abstract

After a reminder about embryonic machines endowed with universal construction and universal computation properties, this paper presents a novel architecture providing additional self-repairing capabilities. Based on the hardware implementation of the so-called Tom Thumb algorithm, the design of this machine leads to a new kind of cellular automaton made of a processing unit and a control unit. The corresponding hardware implementation results from a new and straightforward methodology for the design of self-replicating and self-repairing computing machines of any dimensions.

1 Introduction

The Embryonics project (for embryonic electronics) aims at creating radically new computing machines inspired by Nature and able to grow, to self-repair and to self-replicate [3], [4]. We have previously shown that the Tom Thumb algorithm [5] allows the design of growing and self-replicating structures with universal construction properties. The main goal of this paper is to add self-repairing capabilities to such structures which correspond to artificial cells made of molecules. In order to achieve this goal, each molecule will be implemented as the basic cell of a data and signals cellular automaton (DSCA) [7]. The basic cell of such an automaton is a digital system which results from the interconnection of a processing unit and a control unit.

Section 2 deals with the flags and data that allows the structural configuration and the functional configuration of the artificial cell. It will define all the signals needed for the growth and self-replication of the cell. The self-repairing capabilities will be introduced in Section 3. Using the same flags and data, they lead to structural modification and functional reconfiguration of the artificial cell. Section 4 presents the implementation of the molecule as a basic cell of the data and signals cellular automaton (DSCA). Section 5 will conclude by opening new avenues based on the growth, self-replication and self-repair of embryonic machines.

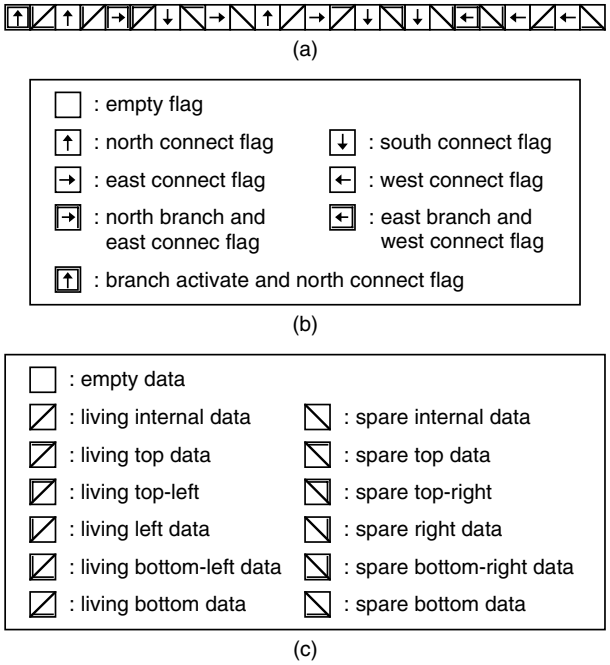

Figure 1. Structural configuration. (a) Configuration string. (b) Flag data. (c) Structural data.

2 Cell growth and self-replication

2.1 Structural configuration

Using the Tom Thumb algorithm [5] in order to configure an artificial cell made of three rows of four molecules, the string of data given in Fig. 1a is applied twice. This string consists of alternate flag data and structural data (Fig. 1b and 1c).

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The data of the string allows the growth of the cell every four time-steps (Fig. 2c) with the help of the signals defined in Fig. 2a and 2b.

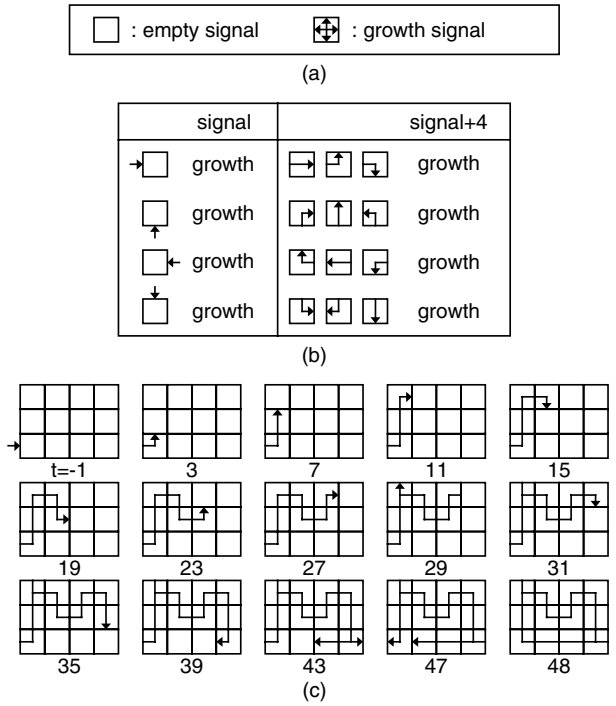

Figure 2. Growth of the artificial cell. (a) Growth signals. (b) Growth transitions. (c) Growth process.

When a close signal (Fig. 4a) is applied to the bottom-right molecule, the artificial cell loads its molecular modes Fig. 3a and its molecular types Fig. 3b at successive time-steps (Fig. 4c). This process takes place according to the transitions depicted in Fig. 4b. The resulting artificial cell is thus made of two living and two spare columns.

2.2 Functional configuration

The functional configuration of the artificial cell is performed by executing the Tom Thumb algorithm again. The configuration string consists now of alternate flag data and functional data (Fig. 5a). In this process (Fig. 5b), the spare molecules are bypassed and only the living ones are configured.

In the structural configuration as well as in the functional configuration, the north branch and east branch flags (Fig. 1b) take care of the self-replication of the artificial cell.

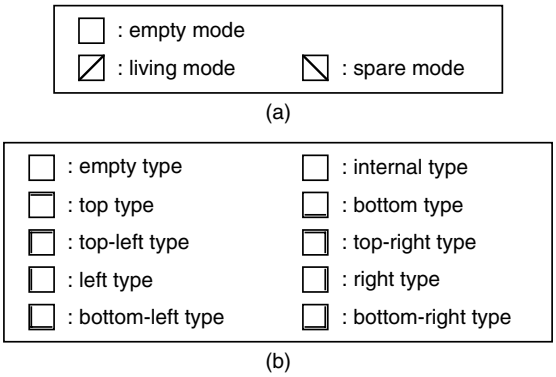

Figure 3. Molecular states. (a) Molecular modes. (b) Molecular types.

3 Cell self-repair

3.1 Structural modification

When a fault happens on a spare molecule, this molecule simply goes in the killed mode (Fig. 6b) and nothing else changes (Fig. 6c). The result of such a fault appears on the bottom-right molecule at time-step t =i (Fig. 6d).

When the fault occurs on a living molecule, it not only instantiates the killed mode for the implied molecule but also sends a repair signal (Fig. 6c) to its right hand living neighbor in order to force it in the repair mode (Fig. 6b). This repair process propagates to the right until it reaches a spare molecule and a global reset of the artificial cell is performed (Fig. 6d).

3.2 Functional reconfiguration

The reconfiguration of the artificial cell involves the Tom Thumb algorithm and the functional string (Fig. 5a). This process applies to the living and repair molecules while bypassing the killed ones (Fig. 7).

3.3 Cell death

When a fault occurs on a repair molecule, or a repair signal on a killed molecule, the artificial cell dies (Fig. 8c). The death of the cell implies an additional signal, the kill signal (Fig. 8a), which leads to an additional mode, the dead mode (Fig. 8b). In Fig. 8d, the death process is activated by a fault occurring on the third molecule of the bottom row.

4 Hardware design

We will now describe the detailed architecture of our basic molecule which corresponds to a data and signals cellular automaton (DSCA) cell [7]. This DSCA cell is designed

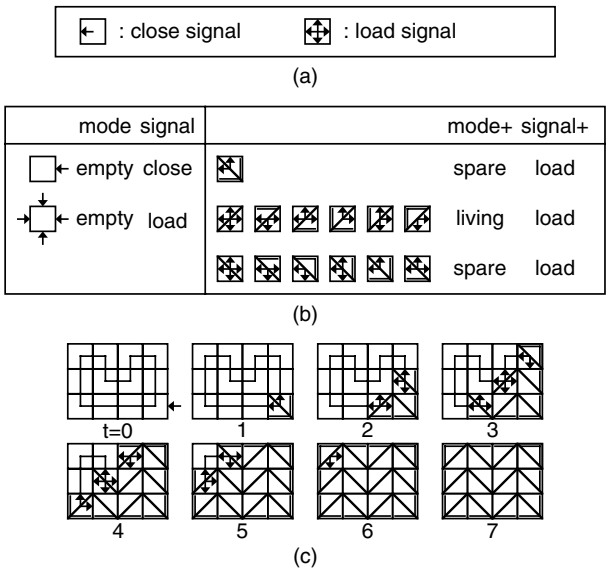

Figure 4. Structure of the artificial cell. (a) Molecular signals. (b) Load transitions. (c) Load process.

as a digital system, resulting from the interconnection of a processing unit handling the data and a control unit computing the signals.

The processing unit is made up of three resources (Fig. 9):

- An input multiplexer DIMUX, selecting one out of the four input data NDI, EDI, SDI or WDI.
- A 4-level stack organized as two genotypic registers GA and GB (for mobile data), and two phenotypic registers PA and PB (for fixed data).
- An output buffer DOBUF producing the output data DO.

The control unit consists of seven resources (Fig. 9):

- An encoder ENC for the input signals NSI, ESI, SSI, and WSI.
- A transmission register I for the memorization of the input selection.
- A decoder DEC defining the mode and the type of the molecule.
- A signal register S.
- A mode register M.
- A type register T.
- A generator GEN producing the output signals NSO, ESO, SSO, and WSO.

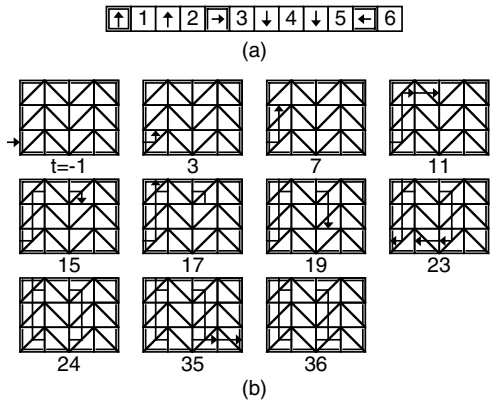

Figure 5. Functional bypass of the artificial cell. (a) Configuration string. (b) Bypass process.

5 Conclusion

The first field of application of our new computing machines is the classical self-replicating automata, such as three-dimensional reversible automata [2] or asynchronous cellular automata [6]. Self-replication is now considered as a central mechanism indispensable for those circuits which will be implemented through the nascent field of nanotechnology [1].

A second, and possibly more important field of application is Embryonics, where artificial multicellular organisms are based on the growth of a cluster of cells, themselves produced by cellular division [4]. These machines not only divide a mother artificial cell in two daughter cells, but are also able to grow and repair a complete organism [3].

The bio-inspired architecture presented in this paper is currently under implementation in a new reconfigurable medium: the BioTissue. This medium is an electronic board with input, output and computation abilities.

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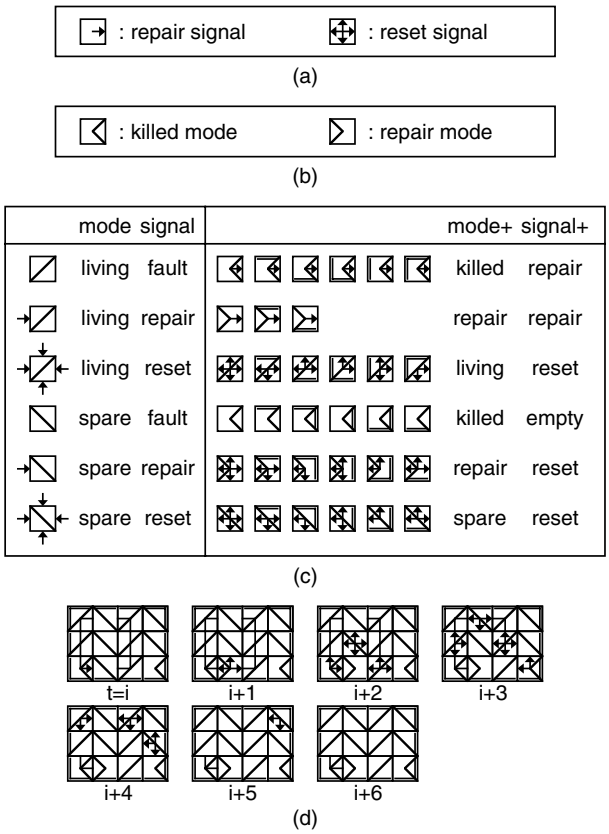

Figure 6. Self-repair of the artificial cell. (a) Additional signals. (b) Additional modes. (c) Repair transitions. (d) Repair process.

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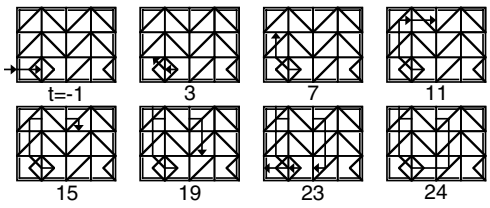

Figure 7. Reconfiguration of the artificial cell.

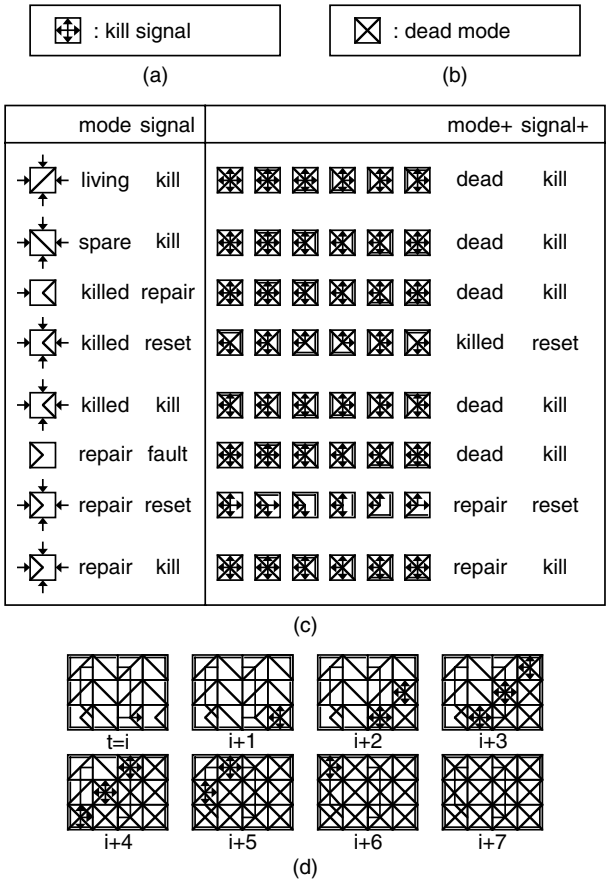

Figure 8. Death of the artificial cell. (a) Additional signal. (b) Additional mode. (c) Death transitions. (d) Death process.

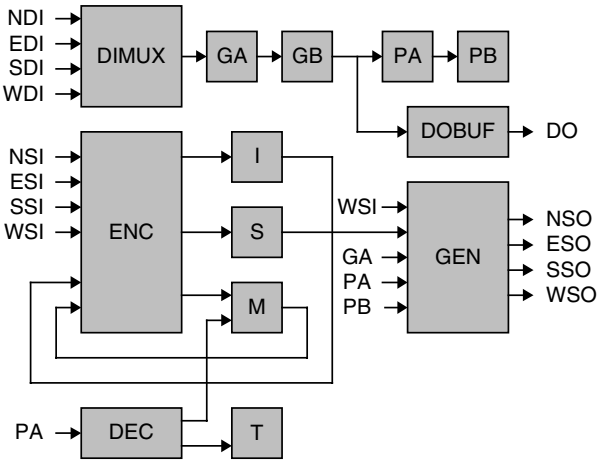

Figure 9. Detailed architecture of the DSCA cell.