On a Brownian Cellular Automaton Implementing Self-Reproducing Loop

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Abstract

An implementation of Self-Reproducing Loops (SRL) on Brownian Cellular Automata (BCA) is proposed in this paper. BCA are asynchronous cellular automata in which certain local configurations propagate randomly in the cellular space, resembling Brownian motion. In the proposed SRL, the signals in the loops and the loop heads can move backward and forward because of the Brownian nature of BCA, thus making it possible to avoid collisions of loop heads.

1. Introduction

A Self-Reproducing Loop (SRL) is a simple structure that is capable of reproducing itself on a Cellular Automaton (CA). Originated by Langton [1], these loops have been extensively studied (e.g. see [2]). They commonly contain structural information that is used in two ways: *interpreted*, as instructions to be executed to construct their offspring, and *uninterpreted*, as data to be copied to the offspring. This resembles the situation in natural systems, such as DNA molecules, which contain genetic information of natural organisms.

SRLs are usually implemented on synchronous cellular automata, that is, all the cells in the cellular space are updated at the same time by a central clock. Synchronous updating enables us to construct SRLs and to analyze their dynamic behavior easily, but, nature is asynchronous: this type of updating scheme has hardly been observed in natural systems. So, if an SRL is treated as an organism in an artificial living system, the behavior of the SRL or of each cell in the cellular space could be driven in an asynchronous manner.

Various models of SRLs working on asynchronous cellular automata have been proposed. Nehaniv showed an implementation of Langton's loop on Asynchronous Cellular Automata (ACA) [3]. This CA is updated by a so-called *marching-soldier scheme*, in which each cell is locally synchronized among its neighboring cells by exchanging information about which cell precedes which in time, but this is not efficient, both in reproduction speed as in the number of states required in cells. Lee et al. constructed a self-reproducing loop on ACA [4] where the reproduction process is conducted sequentially, i.e., one parent loop can produce only one daughter loop. This SRL cannot treat situations in which the construction head of the loop collides with other loop structures. Takada et al. proposed an SRL on Self-Timed Cellular Automata (a type of ACA) in which the SRL is capable of collision detection [5]; however, a significant number of transition rules is required to realize this capability.

In this paper, we propose a scheme to implement an SRL based on Brownian Cellular Automata (BCA). BCA are ACA in which certain local configurations, like signals, propagate randomly in the cellular space, resembling Brownian motion [6]. By exploiting the randomness inherent in BCA in an active way in computation, this model has been proven to be computational universal, i.e., any Turing machine can be simulated on it.

The challenge in this research is that it requires the construction of a self-reproducing mechanism that works flawless even in the presence of asynchronous and random processes, which are hardly found in conventional CA-based SRLs but do have a distinct place in many biological organisms. The proposed SRL includes a self-inspection mechanism: before producing a daughter loop, the mechanism inspects the shape of the mother loop to base the construction on. Therefore, it is capable of self-reproducing a great variety of loop shapes in the cellular space. Though—due to the asynchronous timing—collisions of loop heads may occur when daughter loops are created in the same region, loop heads can move backward and forward because of the Brownian nature of BCA, thus preventing deadlocks these collisions would otherwise give rise to.

2. Brownian Cellular Automaton

A BCA [6] is a two-dimensional asynchronous CA of identical cells, each of which can assume one of a finite number of states at a time. Cells undergo transitions in accordance with transition rules that operate on each cell and its direct four neighbors, shown in Fig. 1. The rules are of a type called Von Neumann neighborhood aggregate rules. In a

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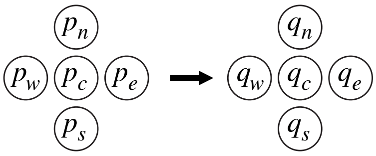

Fig. 1 Transition on BCA

BCA, transitions of the cells occur at random times, independent of each other. Furthermore, it is assumed that neighboring cells of the cells being in transition never undergo transitions at the same time to prevent a situation in which such cells simultaneously write different states into the same location.

We assume that the transition rules are rotational symmetric, i.e., one transition rule has four rotated analogues. Consequently, when we represent the transition in Fig. 1 as

$$(p_c, p_n, p_e, p_s, p_w) \rightarrow (q_c, q_n, q_e, q_s, q_w), \qquad (1)$$

the following three rules also exist:

$$\begin{aligned}(p_c, p_e, p_s, p_w, p_n) &\rightarrow (q_c, q_e, q_s, q_w, q_n)\\(p_c, p_s, p_w, p_n, p_e) &\rightarrow (q_c, q_s, q_w, q_n, q_e)\\(p_c, p_w, p_n, p_e, p_s) &\rightarrow (q_c, q_w, q_n, q_e, q_s)\end{aligned}$$

3. Self-Reproducing Loop based on a Brownian Cellular Automaton

An SRL implemented on BCA in this paper is subject to the following conditions: (1) The loop lacks a protective layer (i.e. unsheathed) and contains only one signal, which is different from Langton's loop, and (2) The loop shape is linear, so it should be a loop and not contain T-junctions in its simplest form, and one T-junction will only occur in a loop at the base of where construction starts. Apart from these conditions, an SRL may have an arbitrary shape. A state of a cell can be in one of the 12 states shown in Fig. 2 and the functions of the states are listed in Fig. 3. The transition rules used are not shown in this paper due to the limitation of page space[1].

The basic element of the loop is a *path*, which is used for transmitting signals. The path lacks a protective layer (i.e. it is unsheathed). An *arm head* attached to the tip of a path operates upon receiving a signal and may create a new path. Figure 4 shows a path and an arm head.

The SRLs in this paper are of a type called *shape-encoding* or *self-inspection* [4, 5, 7], which differs from the original (Langton's) loop where the SRL already contains its construction signals. The SRL contains only one signal and the reproduction procedure is initiated by this signal,

[1]see http://www.eng.u-hyogo.ac.jp/eecs/eecs12/arob10/srlonbca/

Symbol	"Blank"	✣	●	▲	▼	□	◇	◆	✙	○	■	✚
State	0	1	2	3	4	5	6	7	8	9	a	b

Fig. 2 The symbols used to represent the states of a cell

State	Symbol	Function
1	✣	Path.
2	●	Advance the head straight ahead.
3	▲	Advance the head leftwards.
4	▼	Advance the head rightwards.
6 - 7	◇ ◆	Trace and encode the shape.
7	◆	Arm head.
7 - 5	◆ □	Collision detection.
8	✙	Separate a child loop from a parent loop.
9	○	Find next corner and create an arm.
a	■	Padding put on the joint of the arm.
b	✚	Finalize construction.

Fig. 3 States listed with their functions

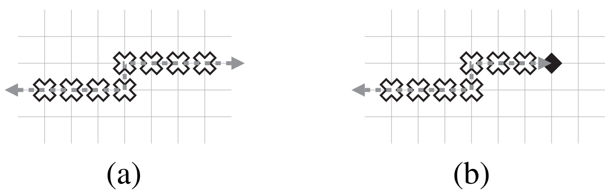

Fig. 4 (a) path and (b) arm head

followed by several other phases. First the structure of the mother loop is scanned, after which construction signals are created based on the scanned information, and this is followed by the construction of a daughter's loop structure. Finally, the umbilical cord between the loops of a mother and her daughter is cut.

The reproduction process is initiated by the signal initially in the loop. This signal can travel bidirectionally in the loop and when it arrives at what would be a left corner of the loop if the signal would travel counterclockwise, this creates an arm head at the front of the arm. This signal also creates a *scanning signal* at its left for scanning the structure of the loop and a *terminator* at its back, which is used for its eventual destruction. The process is shown in Fig. 5, whereby the numbers above/below arrows between the consecutive configurations show the transition rule that is applied.

Most of the self-reproducing process in this SRL is bi-directional, i.e., each process can be traced backward by applying an appropriate transition rule. The only exception concerns the cutting of the umbilical cord.

A scanning signal is bi-directional, i.e., it travels both

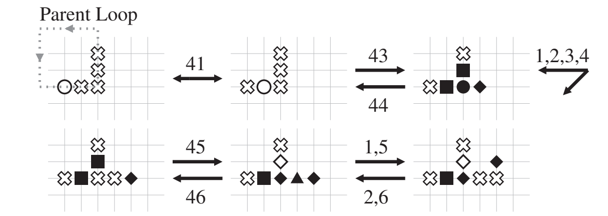

Fig. 5 The start of the self-reproduction process

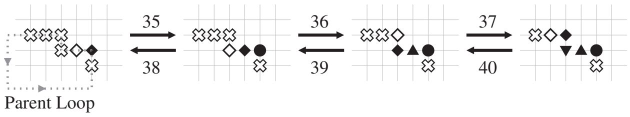

Fig. 6 Process for encoding the structure of the loop

clockwise and counterclockwise in a loop. When this signal moves counterclockwise in one cell, it produces one of three kinds of signals (states 2, 3, and 4) corresponding to the structure of the loop at the location of the scanning signal (see Fig. 6). These signals are *constructing signals*, which also travel in the loop without surpassing other signals and which are used for operating the arm head. A scanning signal can move clockwise in a loop, but this will only be allowed to occur when the scanning signal is at the directly neighboring cell of a construction signal, causing this construction signal to vanish. Moving the scanning signal in one cell clockwise and counterclockwise causes a construction signal being consumed and produced, respectively, so construction signals for a new loop will always correctly reflect the information describing the loop structure.

A construction signal in the state 2, 3, or 4, respectively, creates a new path that is an extension forward, to the left, or to the right of the arm head. Figure 7 shows the process of extending a path by construction signals processed at the arm head.

While the construction signals produced in the mother loop are processed at the arm head, a daughter loop is constructed next of the mother loop, whereby the daughter's shape is the mirror image of the mother's shape relative to the umbilical cord. The final stage of the self-reproduction process consists of cutting the umbilical cord. Figure 8 shows the cutting process. These transitions are irreversible.

Figure 9 shows an example of a cellular space that contains several SRLs. Starting from one initial loop, the loop reproduces itself, thus forming its direct neighbors. Unlike conventional SRLs, the Brownian version occasionally struggles to move forward through the process due to its randomized motion, but on the other hand it is asynchronous like many processes in biological organisms, and

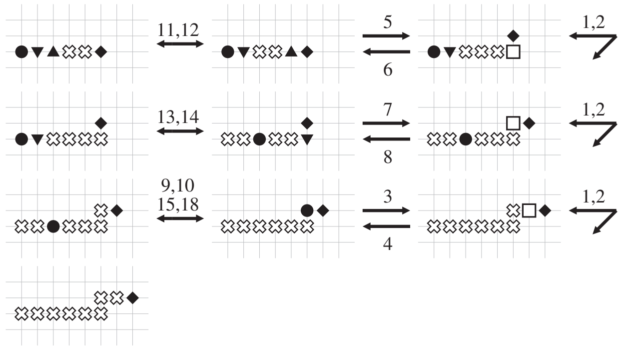

Fig. 7 Extending a path by the construction signals

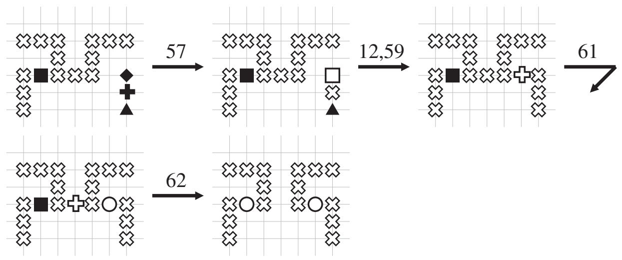

Fig. 8 Cutting process between two loops

deadlocks can be resolved in a natural way.

An example of the resolution of deadlocks is shown in Fig. 10, in which an arm head of one loop collides with the path of another loop. When the collision is detected at the arm head, the arm head stops and no longer accepts any construction signals. The remaining construction signals, which cannot be processed at the arm head, will eventually return to the scanning signal and vanish, thus completing the withdrawal of the loop. After the withdrawal process finishes, the reproduction process starts at another corner of the loop.

4. Conclusions and Discussion

The SRL in this paper can be implemented on a BCA of which cells have 12 states. The number of transition rules is 62, and based on these rules, self-reproduction with asynchronous timing of cells is possible, including the scanning of the loop structure and the avoidance of deadlocks among loops.

The reproduction speed of the SRLs in this paper is not high, due to the fluctuations of signals in the loops, i.e., their movement backward and forward. In the computation by BCA in [6], a configuration called *ratchet* is introduced that prevents signals from moving backward. As a result, the speed of the computation can be accelerated significantly. The introduction of a ratchet-like configuration

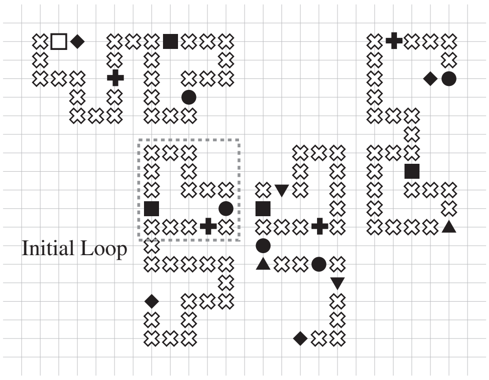

Fig. 9 Self-reproduction of loops

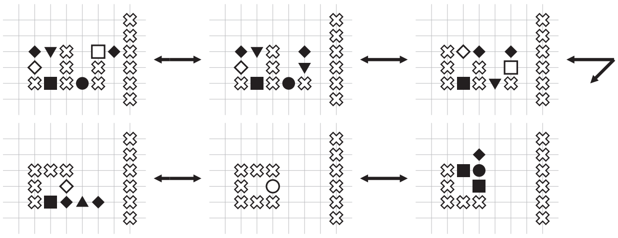

Fig. 10 Arm head colliding with the path of another loop

into the presented SRLs will be an interesting future challenge, because it needs to be applied such that deadlocks are avoided.

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