Theoretical Computer Science 633 (2016) 19–27

Contents lists available at ScienceDirect

Theoretical Computer Science

www.elsevier.com/locate/tcs

Topological evolution for embodied cellular automata

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ARTICLE INFO

Article history:
Received 18 January 2015
Received in revised form 15 May 2015
Accepted 8 June 2015
Available online 11 June 2015

Keywords:
Evolutionary computation
Artificial life
Non-uniform
Cellular automata
Embodied cognition
Topological optimization
Complex systems

ABSTRACT

In this work we introduce a novel method for creating behaviors in cellular automata: optimizing the topology of the cellular substrate while maintaining a single simple update rule. We study the effect of altering the shape of a 3D cellular automaton and local signaling ability of each of its cells on the ability of that automaton as a whole to give rise to emergent locomotion behavior. This system optimizes for the physically embodied interactions between a cellular automaton with an external physically simulated world, rather than optimizing directly for a computational ability internal to the automaton itself. We give each cell in the automaton the ability to have an internal "excited" state, and also the ability to perform a physical action (volumetric contraction and expansion) as a result of that state. We then employ an evolutionary algorithm to optimize for the locomotion ability of the "robot" resulting from the behavior of this embodied automaton. We demonstrate a number of diverse topologies which lead to effective locomotion behaviors in this paradigm. We believe that creating complex behavior from simple rules in a complex substrate not only opens up questions about cellular automata, but also provides insights towards the study of morphological computation and embodied cognition.

1. Introduction

Cellular automata are perhaps the quintessential example of emergent complexity (where we define emergence as the complex collective behavior that arises from the interaction of simple individual components [12]). From Wolfram's elementary cellular automata [30] to Conway's game of life [11], these structures take simple rule sets and iterate them over time and space to create fantastically complex behaviors. In elementary cellular automata, (2 states, size 3 neighborhood), the variety of behaviors produced are the result of the 256 (2^{2^3}) possible rules. These rules are typically applied to a homogeneous cellular substrate to produce the patterns we are accustomed to seeing.

In this work, we seek to explore an alternative method of creating variation in these systems. Rather than exploring the behaviors created by a number of different update rules, we take a single simple rule and vary the topology of the substrate upon which it is applied. The simple rule we chose was that of reaction-diffusion. In the binary-state case, the diffusion-like rule we use is the spacial propagation of excitation through the medium. This means that a cell is activated if and only if at least one of its immediate neighbors was active in the previous time step. Once a cell is excited, it is activated for a small period of time, during which it can excite its neighbors. Following this, the cell experiences a refractory period [19], during which it cannot be re-excited. We take the non-linearities produced by this rule to make up the reaction aspect of

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http://dx.doi.org/10.1016/j.tcs.2015.06.024
0304-3975/

the rule set. This action potential setup creates waves of excitation (rather than allowing for back-excitation, and thus quick homogenization of the activity across the substrate), and is consistent with excitation in natural systems.

Natural instances of this wave propagation technique through excitable tissue suggest the possibility for complex emergent behaviors from this simple model. The human heart is an example of a natural system which uses the diffusion of electrical signals through an excitable muscle to produce behavior. Unlike skeletal muscle, cardiac muscle has gap junctions, which allow the transfer of signals in this manner. Typically this system is well behaved and electric signals from the sinoatrial node (pacemaker) cause the heart to beat once, then the excitation quickly dissipates. However, in some diseases these signals form chaotic and self-sustaining patterns (causing cardiac arrhythmia) [29], opening up the possibility of rich interactions and complex behavior resulting from this rule set.

In the case of cardiac arrhythmia, it is clearly beneficial to remove the complexity of this behavior. In order to do this, cardiologists may use medication to alter the functional (electrical) properties of the tissue [13]. Though often it is necessary to use catheter ablations to change the structural topology of the heart in order to significantly affect the dynamics [6]. This work draws inspiration from the later method – optimizing the topology of our cellular substrate, rather than altering the way that activation propagates over space and time. In this example, attempting to change the tissue properties would be analogous to modifying the update rules to change the behavior of the system. By employing a substrate which can range in behavior from orderly to chaotic, we hope to find an optimal computational abilities within this spectrum, and perhaps around a the phase transition “at the edge of chaos” [18].

Furthermore, we introduce a novel method of evaluating the behavior of a cellular automaton. We situate the automaton within a physical (in this case simulated) environment. By doing so we are able to produce an actionable physical behavior from the signal information propagation through the cellular automaton. We treat each cell as a muscle cell, which volumetrically contracts and expands upon each stimulation. This actionable behavior in the form of physical movement also defines the “fitness” of a given substrate topology, allowing up to optimize these topologies for maximal displacement using evolutionary computation, as is done in [8]. This differs from previous studies which have optimized these automaton for their internal computational abilities only [26,18,20], as we optimize the automata to produce an emergent behavior in a physical simulator, where the behavior is a result of the automata’s interaction with an outside environment. This embodied evaluation method is common within evolutionary robotics, though we are not aware of an evolved robot which fits our definition of a cellular automaton (a grid of cells, each with number of possible states and whose current state is a function of the states of itself and its neighbors).

Upon examining this premise closer, one may realize that this is an exercise in embodied cognition [2], which states that the body plays a fundamental role in the way which the mind processes information and functions. In this extreme case, the mind of the robot does not exist on it’s own, but rather information processing is distributed throughout and within the morphology of the creature. In this sense, the way in which creatures in our system processes information is determined solely through the topology of their body. Given a static environment, one cannot produce changes in the control or behavior of the creature without changing its morphology. By extension of this idea, we imagine this work as an exploration of low-level embodied information processing and morphological computation within the context of robotic design and control.

2. Background

There are, of course, exceptions to the previous notion of cellular automata as homogeneous substrates. Sipper explored non-uniform cellular automata [24–26], looking at one dimensional automata in which each cell could take on a different update rule. This idea of choosing different rule sets at each cell within the automata certainly extends the computational abilities of the automata, and represents a superset of the behaviors created in this paper (if one were to consider the empty cells outside of our optimized topologies as those with rules always leading to the quiescent inactive state). However, as the number of rule sets which must be simultaneously optimized increases, the ability to simultaneously evolve global behavior becomes nearly intractable. To cope with this, Sipper considers a decomposable task (density classification of the initial state) and applies optimization in a completely local manner, receiving performance feedback on the cell and neighborhood levels rather than on the collective behavior of the automata as a whole. In this work, the ability to create richness from just a single rule set helps to keep the problem tractable and (along with our indirect encoding: Section 3.2) allows us to perform optimization on truly global emergent phenomenon, such as the locomotion ability of the entire automata.

Sipper also explored systems in which the automaton could evolve a connection “architecture” in which cells were able to access information from non-neighboring cells [27]. The allowance of information from non-neighboring cells violates the traditional definition of a cellular automaton, in which local interactions collectively produce an emergent global behavior. Though if this assumption is relaxed, it is not surprising that his results suggest allowing such informational “shortcuts” can lead to more efficient computation. Our reaction-diffusion update rule keeps the criteria of local interactions intact.

The idea of using an update rules based on an action potential model is also not novel. Chua and Yang proposed a theory of Cellular Neural Networks, in which a set of neural-network-like nodes are placed in a regular grid, only connected to their immediate neighbors [9]. Gers et al. also demonstrated a cellular automata based neuron model, in which axon and dendrite cells passed signals between spiking neuron cells within a cellular automata. The growth rules of these axons and dendrites were optimized with an evolutionary algorithm to create a substrate that would perform various computations as the signal propagated across the automata [15]. The cardiac modeling work noted above employs a similar type of