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Morphological approach for autonomous and adaptive system: The construction of three-dimensional artificial model based on self-reconfigurable modular agents

Kiwon Yeom [a,b,*]

[a] Human Systems Integration Division, NASA Ames Research Center, Moffett Field, CA 94035, USA
[b] San Jose State University Research Foundation, 210 N. Fourth Street, San Jose, CA 95112, USA

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ABSTRACT

This paper presents a decentralized approach, inspired by biological cells, for the automatic construction of user-defined three-dimensional structures. Using high-level specification as an input, the proposed system enables the guaranteed construction of user-specified structures. By investigating the evolutionary aspects of morphogenesis, which is regulated by the interplay of the cell processes such as differential cell adhesion, gene-regulation, and inter-cellular signaling, an approach was developed that allows for the construction of an arbitrary structure via swarms of identical, independent, and autonomous multi-agents.

1. Introduction

Multicellular dynamic phenomenon refers to any of the processes involved in the development and maintenance of multicellular organisms. Examples include embryonic development, tissue self-assembly, and immune responses. To sustain the characteristic features such as migration, division, inter-cellular communication, and responsiveness to their environment, cells must continually interact with their surroundings [1].

The development of multicellular organisms from a single fertilized cell (embryo) has long fascinated scientists. In the last decade, our understanding of how genes directly interact in developmental processes has greatly improved. As such, important principles in animal morphogenesis such as cell differentiation, the inducing effects of intercellular signaling, the self-organizing properties of adhesion, and cell sorting in morphological growth are now better understood [2].

The field of artificial morphogenesis investigates how the primeval and compact genomes of living organisms can encode the structure of extremely complex multicellular organisms. In general, biological organisms begin their development from a single egg cell and eventually form a distinctive shape through cell differentiation [3]. Before each differentiation, a copy of the genome is symmetrically made and divided from the origin.

The symmetry copy and breaking mechanisms cause the differential gene expression in the descendant cells. However, the embryo is gradually shaped not only as a result of different gene products but also due to the physical interactions between the cell components and between the cells and their environments. The processes allow cells to self-bridge and highlight the discrepancy between the amount of information encoded in the genome and the contribution of self-organizational processes originating in the complex structure of the organism. Furthermore, living systems show a remarkable robustness to perturbations. While this demands better understanding, it raises hopes of employing developmental models to solve various engineering problems and in overcoming the limitations of evolution present in direct encoding schemes [4].

One possible solution might be to use indirect genetic encoding, which takes the form of a developmental process [5,6]. In such an approach a small number of ‘instructions’ in the genotype can encode for a larger phenotype, and the size of the search space can be reduced by consequence of genotype. The power of such evolutionary processes might be improved if the encoding is biased toward locations of the search space, which are more likely to contain good solutions, or if the encoding and the genetic operators generate fitness values that are better suited for search by evolutionary algorithms. Furthermore, a developmental process interacts with the environment, affording the robustness and adaptability observed in living organisms [7].

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[*] Correspondence address: Human Systems Integration Division, NASA Ames Research Center, Moffett Field, CA 94035, USA.
E-mail addresses: pragman@gmail.com, kiwon.yeom@nasa.gov

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In practical terms, the evolutionary process has adopted interactive evaluation to find new swarm behaviors that result in the construction of three-dimensional structures. The interaction between the agents in a swarm population and their surrounding environment ultimately direct their behavior strategies [8,9]. The evolutionary process happens automatically by comparison between the swarm's construction and a predefined three-dimensional structure. Behavior rules, called a *template*, direct agents' flocking and construction activities. Another approach to automatically building user-specified three-dimensional structures uses a bipartite system comprised of passive units, which form the structure, and active units, which manipulate the passive units [10]. The separation into two classes of units allows the passive units to be optimized for structural roles. However, those approaches do not allow for the construction of more general three-dimensional shapes because the rules should be restrictive than it strictly needs to be, and the separated classes cause mutual conflict.

In this research, we use a simple genetic encoding approach and dynamic developmental system to direct the self-construction of multicellular agents. It is based on the gene expression principle and cellular differentiation. The proposed evolutionary system for multicellular agents, describe in this paper, is capable of dynamic reconfiguration. For example, a reconfiguration process occurs when errors are detected in the system, when the surroundings change, or when the circuit is expanded with new cells [11]. Generally, direct genetic encodings are not well suited for these kinds of scenarios since the number of elements in the system must be known in advance. Furthermore, these elements cannot change throughout the life of the system because the gene encoding information cannot be easily modified. Direct genetic encodings are also limited in terms of scalability due to the fixed size of encodings in practical solutions.

The proposed system is intended to address these issues while focusing on computational resource efficiency and execution speed. A short review and a new classification of developmental systems in an evolvable system are given in Section 2. We describe general problems and assumptions in Section 3 and present the model of development and morphogenetic system in Section 4. Section 5 investigates system's capacity to evolve two-dimensional structures of various complexities. In Section 6, we describe the evolutionary model. We discuss the biological implications with experimental results in Section 7 and draw the conclusions and outline future work in Section 8.

2. Related works

The problem of automating three-dimensional collective construction, as formulated in this paper, is related to a number of topics in self-reconfigurable modular robotics and morphogenesis. In this section, we discuss related work in modular robotics and programmed self-assembly.

Ref. [12] describes a robot with the ability to manipulate passive cubic blocks. The system's creators focus on the hardware design of the robot but do not consider automatic control of the robot. Everist et al. [13] discuss a two-dimensional self-assembly system using self-mobile pucks to assemble passive struts. Ref. [14] introduces the inter-robot communication method with cubic blocks. In Ref. [15] a very simple approach for the manipulation of circular objects is introduced. Ref. [16] proposes a polymer foam based hardware system for building terrestrial robots.

Many other works address an emergent system with identical mobile units that are required to organize and rearrange themselves autonomously into a given or desired configuration via a distributed mechanism [17–19]. Another related area is self-assembly, which involves the automatic formation of a user specified shape. Ref. [20] presents the hardware design for cube based self-assembly in three-dimensional spaces.

It is also worth discussing work in automatic construction that takes the swarm and morphologies' approach. Many morphology-based approaches have been proposed. One of the oldest models is represented by L-Systems proposed in [21]. L-Systems introduced the notion of cell signaling and proposed a computational plant growth model. Kaufmann proposed Random Boolean Networks (RBN's) as a model of genetic regulatory networks [22]. He proposed that the attractors of RBN's (i.e. the stable states) were able to be interpreted as the different ‘cell types’ of the organism [3] and Unsal and Bay [23] developed a evolutional model for convex and non-convex shapes using two-dimensional cellular automata. They applied the grammar tree as developmental instructions at each node. Ref. [14] describes an evolvable computational organism using Cartesian Genetic Programming. Their goal is to develop a cell division mechanism, which allows a cell to generate multi-cellular organisms.

Recently, biologically inspired models for cellular development have been introduced. In some literature, the developmental process takes place on a two-dimensional lattice with cells at fixed locations (e.g., [5,24]). Other papers show that the resulting shape of the cellular developmental process is determined by the physical interactions between membranes [23,11]. Some approaches present elastic interactions between cells [2]. However, three-dimensional approaches still remain rare. Three-dimensional spaces generate more degrees of freedom, which complicates the task of cellular development.

3. General problems and assumptions

Our ultimate goal in the present work is to design an automated three-dimensional construction system as follows: firstly, the number of agents involved the construction of the structure will be unspecified. Secondly, the agents are expected to proceed with the construction of a three-dimensional structure without further intervention. A high-level description of the user-specified structure, in the form of an image, is the only required input information. To this end, we define a set of rules corresponding to the shape image (or map). Accordingly, the agents will move in the appropriate direction, bind with each other, and achieve the target structure.

We assume the three-dimensional space is a weightless or micro-gravity environment, and the agent can move freely in any direction in the environment without any limitations. Since dealing with gravity would complicate a variety of considerations, we leave this issue for future work. An example of one of the complications includes constraints on the agent's movement and construction (e.g. climbing the structure and stabilization of the structure). Nevertheless, we can still imagine potential applications of this self-construction system in environments such as outer space.

Once a partial structure is built, we assume that the agents will be able to move along its surface in any direction and attach to other agents that are fastened at sites. There is no centralized control, and coordination is implicitly controlled via the structure being built. Agents are cubic blocks, which are the same as modular robots. The reason we use cubic blocks is for the convenience they afford in a Cartesian coordinate system and because their movements are easy to control (generally six directions only). Moving agents can communicate with physically attached agents to share the coordinate system and to decide whether attachment at a site is possible or not. Each agent stores the shape map into its static memory, and we assume that the