Making a Self-Feeding Structure by Assembly of Digital Organs

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Abstract. In Nature, the intrinsic cooperation between organism's parts is capital. Most living systems are composed of organs, functional units specialized for specific actions. In our last research, we developed an evolutionary model able to generate artificial organs. This paper deals with the assembly of organs. We show, through experimentation, the development of an artificial organism composed of four digital organs able to produce a self-feeding organism. This kind of structure has applications in the mophogenetic-engineering of future nano and bio robots.

1 Introduction

Most living systems are composed of different organs. Cooperation between organs allows them to optimize the exploitation of environmental resources. Its role is crucial for survival in a complex environment. Several works on digital organs development already exist mainly based on two methods: shape generation, which is the most widely discussed, and function generation. Whereas the first is usually based on artificial Gene Regulation Networks (GRN) and, in recent years, tries to be the most biologically plausible as possible, the second method is usually based on cellular automata or block assembling and is more bio-inspired than biologically plausible.

Our previous research dealt with making isolated digital organs. We developed a bio-inspired model able to produce goal-directed organisms starting from a single cell. The aim was to make an organ library. We now present the assembly of two kinds of organs: producer-consumers and transfer systems. Assembling these organs produces a self-feeding structure and gives the organism a potentially limitless survival capacity.

The paper is organised as follows. Section 2 gives the related work about artificial development and artificial creature production. Section 3 summarizes the model, already presented in [4]. Section 4 details the experimentation of a self-feeding structure with particular emphasis on environmental parameters. Section 5 discuss the possible application of such a developmental model for morphogenetic engineering of future bio and nano systems. Finally, we conclude by outlining possible future work on this creature.

2 Related works

Over the past few years, more and more models concerning artificial devolpment have been produced. A common method for developing digital organisms is to use artificial

regulatory networks. Banzhaf [1] was one of the first to design such a model. In his work, the beginning of each gene, before the coding itself, is marked by a starting pattern, named "promoter". This promoter is composed of enhancer and inhibitor sites that allow the regulation of gene activations and inhibitions. Another different approach is based on Random Boolean Networks (RBN) first presented by Kauffman [12] and reused by Dellaert [7]. An RBN is a network where each node has a boolean state: activate or inactivate. The nodes are interconnected by boolean functions, represented by edges in the net. Cell function is determined during genome interpretation.

Several models dealing with shape generation have recently been designed such as [6, 14, 17, 2, 13, 11]. Many of them use gene regulation and morphogens to drive the development. A few produce their own morphogens whereas others use environment "built-in" morphogens. Different shapes are produced, with or without cell specialisation. The well-known French flag problem was solved by Chavoya [2] and Knabe [13]. This problem shows model specialisation capacity during the multiple colour shifts.

In their models, produced organisms have only one function: filling up a shape. Other models, most often based on cellular automata or artificial morphogenesis (creatures built with blocks), are able to give functions to their organisms [16, 10, 8]. Here, creatures can walk, swim, reproduce, count, display... Their goals are either led by user-defined fitness objectives that evaluate the creature responses in comparison to those expected or only led by their capacity to reproduce and to survive in the environment.

The next section presents our developmental model. It is based on gene regulatory networks and an action selection system inspired by classifier rule sets. It has been presented in details in [4].

3 *Cell2Organ*: a cellular developmental model

3.1 The environment

To reduce simulation computation time, we implement the environment as a 2-D toric grid. This choice allows a significant decrease in the simulation's complexity keeping a sufficient degree of freedom.

The environment contains different substrates. They spread within the grid, minimizing the variation of substrate quantities between two neighbouring crosses on the grid. These substrates have different properties such as spreading speed or colour, and can interact with other substrates. Interactions between substrates can be viewed as a great simplification of a chemical reaction: using different substrates, the transformation will create new substrates, emitting or consuming energy. To reduce the complexity, the environment contains a list of available substrate transformations. Only cells can trigger substrate transformations.

3.2 Cells

Cells evolve in the environment, more precisely on the environment's spreading grid. Each cell contains sensors and has different abilities (or actions). An action selection

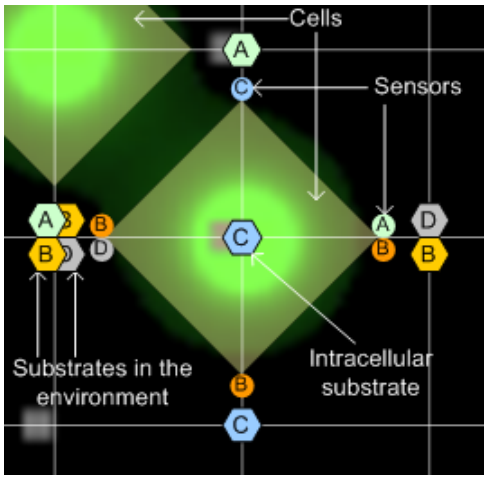

Fig. 1. The cell plan in its environment. It contains substrates (hexagons) and corresponding sensors (circles)

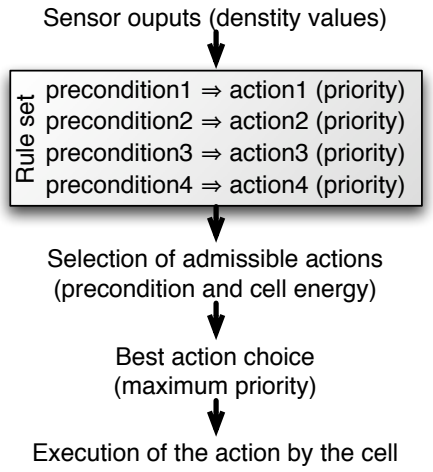

Fig. 2. Action selector functioning: sensors and cell energy are used to select admissible actions. The best action is chosen according to the rule priority.

system allows the cell to select the best action to perform at any moment of the simulation. Finally, a representation of a GRN is available inside the cell to allow specialization during division. Figure 1 is a global representation of our artificial cells.

Each cell contains different density sensors positioned at each cell corner. Sensors allow the cell to measure the amounts of substrates available in the cell's Von Neumann neighbourhood. The list of available sensors and their position in the cell is described in the genetic code.

To interact with the environment, cells can perform different actions: perform a substrate transformation, absorb or reject substrates in the environment, divide (see later), wait, die, etc. This list is not exhaustive. The implementation of the model enables a simple addition of actions. As with sensors, not all actions are available for the cell: the genetic code will give the available action list.

Cells contain an action selection system. This system is inspired by the rule set of classifier systems. It uses data given by sensors to select the best action to perform. Each rule is composed of three parts: (1) The *precondition* describes when the action can be triggered. A list of substrate density intervals describes the neighbourhood in which action must be triggered. (2) The *action* gives the action that must be performed if the corresponding precondition is respected. (3) The *priority* allows the selection of only one action if more than one can be performed. The higher the coefficient, the more probable is the selection of the rule. Its functioning is presented in figure 2.

Division is a particular action performable if the next three conditions are respected. First, the cell must have at least one free neighbour cross to create the new cell. Secondly, the cell must have enough vital energy to perform the division. The needed vital

energy level is defined during the specification of the environment. Finally, during the environment modelling, a condition list can be added.

3.3 Action optimisation

The new cell created after division is completely independent and interacts with the environment. During division, the cell can optimize a group of actions. In nature, this specialization seems to be mainly carried out by the GRN. In our model, we imagine a mechanism that plays the role of an artificial GRN. Each action has an efficiency coefficient that corresponds to the action optimization level: the higher the coefficient, the lower the vital energy cost. Moreover, if the coefficient is null, the action is not yet available for the cell. Finally, the sum of efficiency coefficients must remain constant during the simulation. In other words, if an action is optimized increasing its efficiency coefficient during division, another (or a group) efficiency coefficient has to be decreased.

The cell is specialized by varying the efficiency coefficients during division. A network represents the transfer rule. In this network, nodes represent cell actions with their efficiency coefficients and weighted edges representing efficiency coefficient quantities that will be transferred during the division.

3.4 Creature genome

To find the creature best adapted to a specific problem, we use a genetic algorithm. The creature is tested in its environment. It returns the score at the end of the simulation. Each creature is coded with a genome composed of three different chromosomes: (1) the list of available actions, (2) an encoding of the action selection system and (3) an encoding of the gene regulation network.

3.5 Example of generated creatures

Different creatures have been generated using this model. For example:

- A *harvester*: a creature able to collect a maximum of a substrate scattered all over the environment and transform it into division material and waste. The creature has to reject the waste because of a limited substrate capacity.
- A *transfer system*: presented in [4], a creature able to move substrate from one point to another. This creature is interesting because it has to alternate its behaviour between performing its function and developing its metabolism to survive.
- Different *morphologies*: also presented in [4], such as a starfish, a jellyfish or any user-designed shape. Once again, the organism must develop its metabolism to be able to perform its function.

All creatures have a common property: they are able to repair themselves in case of injury [5]. This feature is an inherent property of the model. It shows the phenotype plasticity of produced creatures.

In the next section, we present the features obtained by producing new organisms and putting them in the same environment. We design an environment wherein the organism will be composed of four organs. Once assembled, their organs will make a self-feeding structure that will allow the organism to maintain its life endlessly. Before that, the organism must develop a sufficient metabolism to start the chain.

4 Experiments: self-feeding structure

In order to produce a cycle, the organism is composed of two kinds of organs: transfer systems close to the one previously presented and organs able to transform a substrate into another and to position precisely the produced substrate (to be transferred by a transfer system). The global functioning is introduced by Figure 3.

Section continuation is organised as follows. First, we will describe clearly the different organs, detailing the global environment and the different possible actions for each organ. Then we will show and discuss the organism obtained.

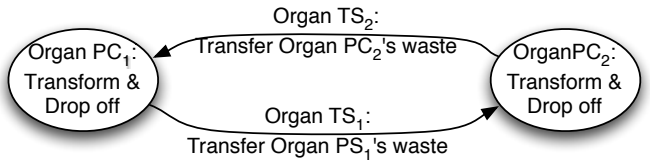

Fig. 3. Functioning diagram of the organism. It is composed of two kinds of organ: producer-consumer organs PC_1 and PC_2 able to transform substrates and to position them in a particular place; transfer organs TS_1 and TS_2 able to transfer substrates from one point to another.

4.1 Experimentation parameters

Description of the environment

The environment is composed of 3 different substrates:

- *E* (represented in blue on the next figures) that will be used by the organism to develop its metabolism,
- *A and B* (respectively represented in red and yellow on the next figures) substrates that will be used by the organism to produce the self-feeding structure.

Three substrate transformations are available:

- $E \rightarrow energy$ produces energy using water,
- $A \rightarrow B + energy$ produces B substrate plus energy using one unit of A,
- $B \rightarrow A + energy$ produces A substrate plus energy using one unit of B.

50 units of A substrates are positioned near PC_1 and 50 units of B substrates near PC_2. Organ PC_1 has to transform the substrate A into B and must position it at the entrance of organ TS_1, which transfers the B substrate on the entrance of organ PC_2. Organ PC_2 has to permorm the opposite operation to that of organ PC_1: it transforms B substrate into A and has to put the result at the entrance of organ TS_2, which drives the A substrate back up near organ PC_1. Because all their actions provide energy to the cells, the obtained organism can work endlessly. With the purpose of producing the self-feeding structure, each organ has first been developed individually. Each kind of organ has a different list of possible actions.

Action	Cost	Needs	TS_1	TS_2	PC_1	PC_2
Divide to NorthEast	30	1 unit of E	X	X	X	X
Divide to NorthWest			X	X	X	X
Divide to SouthEast			X	X	X	X
Divide to SouthWest			X	X	X	X
Transform $E \rightarrow energy$	-30	1 unit of E	X	X	X	X
Transform $A \rightarrow B$	-50	1 unit of A			X	
Transform $B \rightarrow A$	-50	1 unit of B				X
Absorb E from North	2	Cell must contain less than 7 substrat units		X	X	X
Absorb E from South	2			X	X	X
Absorb E from East	2			X	X	X
Absorb E from West	2			X	X	X
Absorb A from North	-2	Cell must contain less than 7 substrat units		X	X	X
Absorb A from South	-2			X	X	X
Absorb A from East	-2			X	X	X
Absorb A from West	-2			X	X	X
Absorb B from North	-2	Cell must contain less than 7 substrat units	X		X	X
Absorb B from South	-2		X		X	X
Absorb B from East	-2		X		X	X
Absorb B from West	-2		X		X	X
Evacuate A from North	-0.5	Cell must contain at least one unit of A		X	X	X
Evacuate A from South	-0.5			X	X	X
Evacuate A from East	-0.5			X	X	X
Evacuate A from West	-0.5			X	X	X
Evacuate B from North	-0.5	Cell must contain at least one unit of B	X		X	X
Evacuate B from South	-0.5		X		X	X
Evacuate B from East	-0.5		X		X	X
Evacuate B from West	-0.5		X		X	X
Do Nothing	1	-	X	X	X	X

Table 1. Table of possible actions of different organs of the self-feeding structure. All organs do not have all the action activate to accelerate the convergence process of the genetic algorithm.

Possible actions for the organs

The table 1 gives the possible actions for the different organs TS_1, TS_2, PC_1 and PC_2. Some actions are inactivated to accelerate the convergence process of the genetic algorithm. However, organs have the possibility to divide to all directions to increase the degree of freedom. The energy cost of actions, except for division, substrate E absorption and wait actions, are negative to give the stucture to produce energy during the cycle.

4.2 Results

We compute each organ in a separate environment. Four cells containing the genetic code of their corresponding organ are then assembled to the environment. They evolve with the aim of generating a self-feeding structure. Figure 4 shows the development and the behaviour of the organism. It is worth mentionning that for each kind of organ,

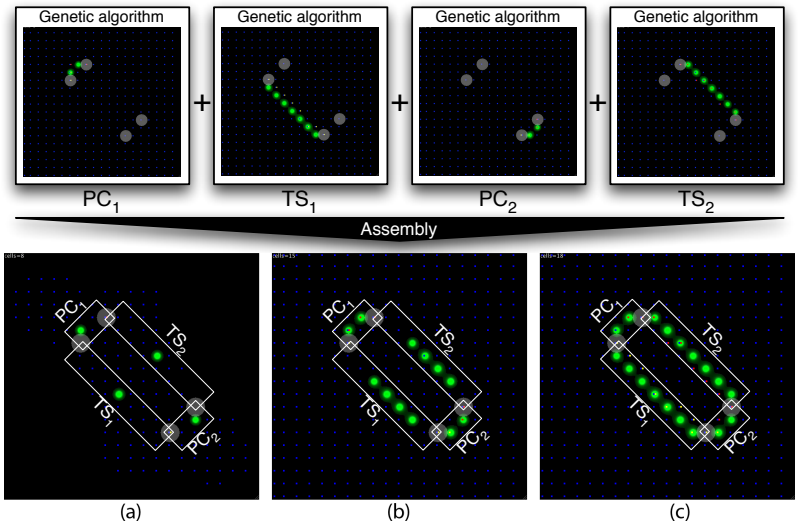

Fig. 4. Result of the assembly of the 4 different organs. (a) Beginning of the simulation: 4 cells that contain the genetic code of each organ are positioned in the environment. (b) Organ growth: while the 2 producer-consumer organs have finished their development and start their work, the transfer systems continue their growth. (c) All organs have finished their development and a self-feeding structure is made. While producer-consumer organs continue their work, transfer systems start the transfer to feed other organs with new substrates.

different strategies emerge to reach the goal. For example, organ PC_1 transfers the initial substrate near the goal before transforming it into the final substrate whereas organ PC_2 transforms the substrate before transferring the result to the right place.

The obtained organism works as expected one[1]. The regulation network regulates correctly the size of the transfer systems whereas the organs that transform the substrate develop the different action selection strategies to reach their goals. Detailed functioning of organs is given by figure 5. Organ PC_1, on the top left, transfers A substrate (in red) to the second cell before transforms it into B and reject the result in the right position. Organ PC_2 adopts the opposite strategy: it absorbs substrate B, transforms it in the first cell and transfers the resulting substrate A to the final position. Organ TS_1 and Organ TS_2 use serial absorption and rejection to move the substrate from the exit of an organ to the entrance of the opposite organ.

Curves presented in figure 6 show the evolution of the number of cells and the water quantity in the environment. The quantity of E substrate strongly decreases at the beginning of the simulation, before the initialisation of the cycle (stage 1). Different organs use water to start their metabolism. When the cycle starts (stage 2), organs use the cycle as metabolism. Organs still consume water to produce energy that will be stocked for the future. The curve presented in figure 7 shows the ratio of A and B substrates. B substrate quantity slowly decreases. This proves an efficiency difference

[1] Videos of this organism development and of each organ functioning seperately are available on the website http://www.irit.fr/∼Sylvain.Cussat-Blanc

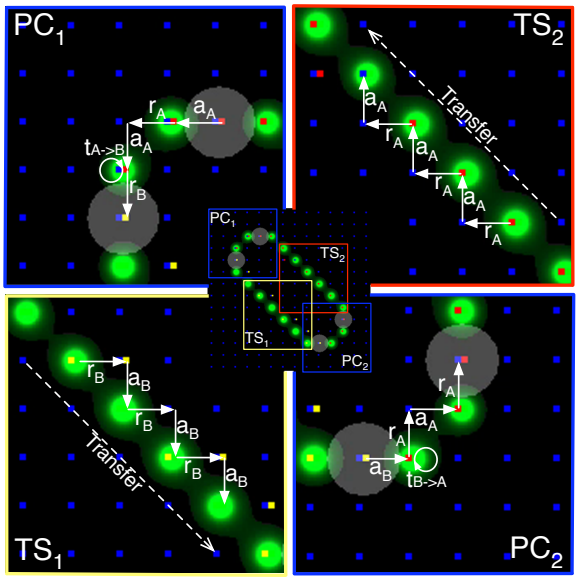

Fig. 5. Detail of the organism functioning. Acronyms on arrows correspond to actions accomplished by cells: r_A means "reject A", a_B "absorb B" and $t_{A\rightarrow B}$ "transform A into B".

in the organs: organ PC_1 converts A into B more slowly than organ PC_2 does the opposite. Even if the difference is small, this curve shows that the cycle is not endless: after a long period of time, B substrate will disappear and the cycle will be broken.

5 Discussion

Developmental models that take into consideration the organism's metabolism should have many applications in the near future. Self-assembly, self-repairing and self-feeding, or more generally self-*, properties are important for the future bio and nano robots. Many works are nowadays in progress to develop artificial cells [15, 9] and nano modules for the future modular robots [3, 18, 19].

In synthetic biology, which will produce future bio-systems, researchers are today working on modifying the genome of different bacteria to make them produce particular proteins. Those proteins are used to express a particular function in a cell. Some building blocks of this chemical self-assembly are already in place and many others have to be found [9]. In the next twenty years, it seems to be possible to build a cell able to replicate itself and to have a group of possible actions. Developmental models, especially those that include metabolism, would be necessary in order to find the genome that will allow the cell to perform its asked goal with the minimum set of actions. They will have to be more biological plausible than bio-inspired because of the constraints imposed by Nature. In other words, a model like *Cell2Organ* will have to be more precise (take into consideration physics, better simulate chemical reactions...) to be acceptable for this kind of applications.

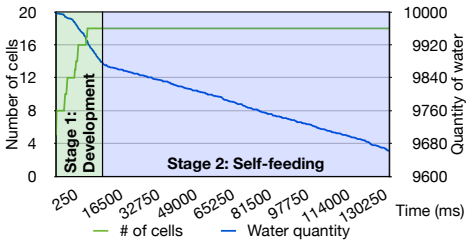

Fig. 6. Number of cells (left ordinate) and quantity of water (right ordinate) in the environment in function of time (abscissa).

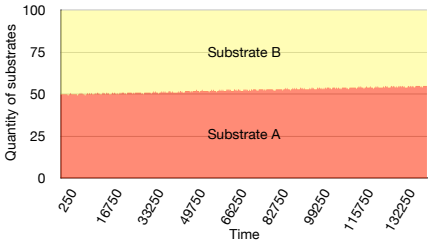

Fig. 7. Evolution of A and B substrate quantity ratio. The B substrate quantity decreases: Organ PC_2 is more efficient than PC_1.

Our model is applied more in the domain of nano robots, or more precisely mesosystems. We are now able to work on atoms to modify the molecules' material structure. We can imagine that, in some years, modular robotics like Lipson Molecube robots [19] could have a size of a couple of nanometres. Building structures composed of thousands of their units able to accomplish different actions would be possible. Such developmental models will be interesting to use in order to learn those robots to self-build their structures and functions. In this case, a bio-inspired model like the one presented in this paper could be sufficient because each robot module could include human-designed functions. Metabolism could be an interesting feature of such a robot in order to allow itself to use environmental resources (like glucose that is contained in many natural organisms for example) to produce their own energy, essential to perform their tasks.

6 Conclusion and future works

In this paper, we present an original result of the developmental bio-inspired model *Cell2Organ*. After making an artificial organ library, we test cooperation between organs. The experimentation shows the development of an artificial organism, composed of four digital organs. The cooperation of its organs creates a self-feeding structure. This kind of structure, with the self-repairing properties presented in [5], could be interesting for a the morphogenetic-engineering approach of future bio and nano robots.

Continuations of this work are multiple. First of all, we are currently starting the development of the organism with four cells, one for each organ. We want to develop the organism starting from only one cell. With this purpose, we are working on a "pre-organism" able to position cells on the four starting positions of the final organs. The organism will have to switch it genome to the different organs' genomes and, finally, to resorb itself so as not to interfere with the organism's evolution.

We are also working on making different layers of the simulated environment. A physical layer will allow us to develop our organism at the same time in a physical world, with all its properties and the current "chemical" world to maintain the metabolism of the creatures. A hydrodynamic layer will simulate substrate diffusions more efficiently. For example, this layer will allow a cell to expulse a substrate with a

chosen strength to position it in a particular place. It will also simulate fluid flows. Cells will have to adjust their behaviour according to new data.

Acknowledgment: Experiments presented in this paper were carried out using ProActive, a middleware for parallel, distributed and multi-threaded computing (see http://proactive.inria.fr), and the Grid'5000 French experimental testbed (see https://www.grid5000.fr)

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