A Self-Organizing System with Cell-Specialization

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Abstract— **For the study of evolutionary system, we have already proposed several models. In this paper, we are concerned with a different type of evolutionary system, the cell-specialization.**

As seen in hydras, the cell-specialization is one of the very important types of self-organization. In the process of the cell-specialization, each cell which has the same DNA is specialized to have its roles, and a whole system which consists of these cells comes to have a high advanced function. We propose a kind of coding (something like DNA), "*a system description*" which makes this possible.

Using the system description, we built a hardware model which shows the validity for slef-organization, and also did some computer simulations which shows this can be used for evolutionary systems.

TABLE I
An example of the system description.

C_1	C_2	C_3	C_4	Function
1	-	1	0	F_1
0	1	0	0	F_2 F_3
0	0	1	-	F_4
1	1	0	1	F_3

I. Introduction

This study is a "synthetic approach" to the evolutionary system. If a constructed model is similar to the original system in real world, the model will contain the essence of the system. We call this type of studies a synthetic approach. In the approach, it is desirable to simulate everything in perfect manner, but it is difficult for evolutionary system. We have proposed some models, and the model proposed in this paper is one of them. After enough of these trials, we believe we can clarify the mechanism of evolutionary system.

In this paper, we focus on the cell-specialization as seen in the following result of biological experiments. A hydra, the fresh-water coelentrate, is decomposed into cells. Then they are gathered by a centrifugal machine and are put into liquid whose temperature and constitution fit a hydra to live. In several days, a hydra is reconstructed and becomes alive. Through the reconstruction, the cells do not recover the original positions, but respecializations occur.

When a living thing grows from an egg-cell, fissions of cells occur, and the cells are specialized variously to make a living thing. In hydra's reconstruction, the cells are repsecialized to make a hydra according to the same DNA in every cell. Let us start from the point of view that a cell is an unit of life, and that a living thing is a congregation of cells. Even a higher animal has such an aspect. The mechanism of a hydra (it is also seen in some kinds of fungi) is characteristic of this viewpoint. And DNA plays an important role for this mechanism. We would like to construct a model for the mechanism of the cell-specialization and to study self-organization of a living thing.

We have already presented two papers in ICEC. In the first paper[2], we proposed a model for self-organization, where various robots (systems) are automatically produced from five kinds of elements through mating and mutations. We devised a "robust" system description for this purpose, and this was the aim of this paper. With this system description, the system (robot) does not lose the meaningful function through mating and mutations. In the second paper[3], we proposed "a learning machine that evolves" where a Perceptron-like learning machine obtains a proper set of feature-detecting cells through mating, mutations and natural selections. The paper focused on the mechanism of natural selections.

This paper aims to realize the mechanism of cell-specialization. We propose the system description that enables this type of self-organization. We also show its validity by a hardware model, and its robustness by computer simulations.

II. System Description

We treat the model where each system consists of some

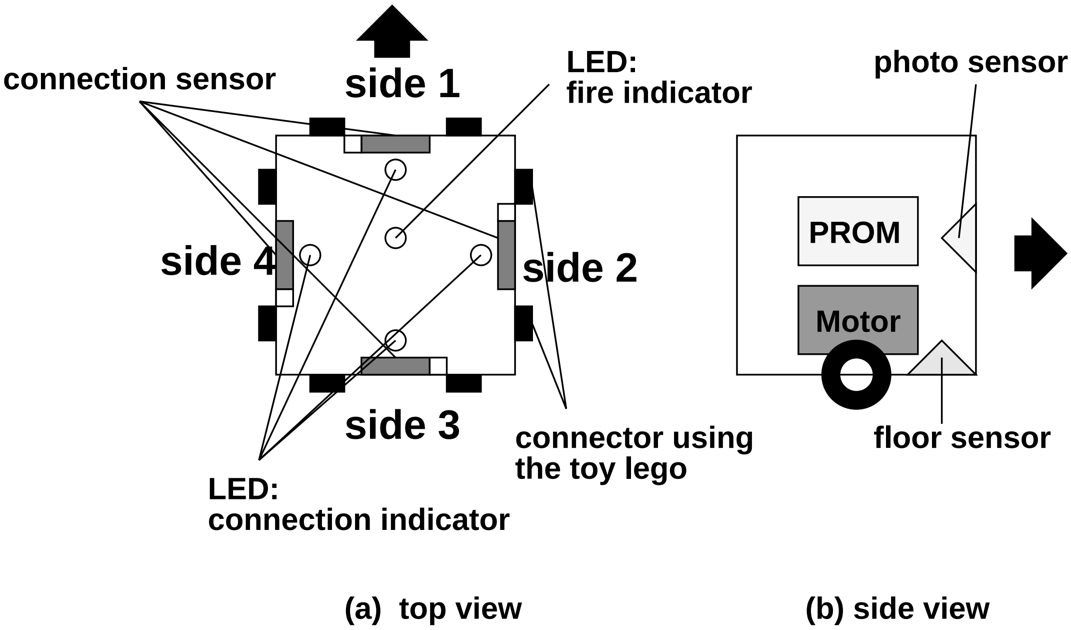


Fig. 1. A Cell. The big black arrow shows the direction of a cell to proceed.

cells. A cell includes actuators and sensors (Detail of cells will be given in Sec.III). To construct the system, we need a kind of blueprint, and we call this "the system description."

The system description is the set of IF-THEN rules for every cell. Table I is an example of the system description. The left side of the table shows conditions of the cell , and the right side shows functions. In the table, "1" is TRUE , "0" is FALSE and "-" is "don't care." First line of the table shows that if condition C_1 and C_3 are TRUE and condition C_4 is FALSE , then execute function F_1 (condition C_2 is "don't care"). For example, the connectivity of the cell is considered as the condition, and the switching the motor is considered as the function. The details of other functions and conditions will be given in Sec.IV.

As a new cell is connected, the condition of the cell is changed, and hence the function that the cell executes also changes. The cell is specialized because of the change of the condition.

Sometimes a system description includes meaningless and redundant parts, that is, functions to indicate to connect where it is impossible physically to connect, or conditions which never happen. It is, however, not harmful, so we leave them as it is. They act important roles in mating and mutations, and we give the detail in Sec.V.

III. Image of Hardware Model

In the hardware model, the cells are cubic elements as in Fig.1. Each cell has the same system description and can be specialized. Because it is hard to realize specialization physically, the specialization is realized in the way that every cell has all functions and some of them are activated according to the system description.

When one of the cells becomes active autonomously, this cell (core cell) indicates to connect other cells on some sides by LED. We supposed the orientations of the cells are the same. Therefore, side1 of a cell will be connected to side3 of another cell, and side2 will be connected to side4. And also side1 corresponds to the direction of the cell to proceed. The cell connected to the core cell (or the block including the core cell) is specialized and indicates to connect other cells according to its system description. In this way, cells are assembled, and the complete structure of the system is realized when no cell indicates to connect other cells.

IV. Hardware model of self-organizing system

As illustrated in Fig.1, a cell has a motor, a photo sensor, a floor sensor, four connection sensors and a PROM where the system description is stored. Cells can sense their conditions through sensors.

The following are the conditions which sensors can give.

$$\textbf{Floor sensor: } \mathbf{S_0} = \begin{cases} 0, \text{if floor is black.} \\ 1, \text{if floor is white.} \end{cases}$$

$$\textbf{Photo sensor: } \mathbf{S_1} = \begin{cases} 0, \text{if no light is received.} \\ 1, \text{if light is received.} \end{cases}$$

Connection sensors:

$$\mathbf{C_1}, \cdots, \mathbf{C_4} = \begin{cases} 0, \text{if no cell is connected to side1} \cdots 4, \\ \quad \text{respectively.} \\ 1, \text{if a cell is connected to side1} \cdots 4, \\ \quad \text{respectively.} \end{cases}$$

Conditions of neighbour cells:

$$\mathbf{N_1}, \cdots, \mathbf{N_4} = \begin{cases} 0, \text{if the cell connected to side1} \cdots 4 \\ \quad \text{does not fire.} \\ 1, \text{if the cell connected to side1} \cdots 4 \\ \quad \text{fires.} \end{cases}$$

The following are functions which cells can execute.

Connection indicator:$G_1, \cdots, G_4$
G_i indicates that a cell should be connected to side i.

Fire:F F means that the cell should fires. As a cell fires, a motor runs.

The index numbers of C_i, N_i and G_i show directions: 1 is front side, 2 is the right, 3 is the rear, and 4 is the left (See Fig.1(a)).

Cells are assembled to a structure according to a system description, and the structure has a specific function. We call it a system (robot). Table II is an example of a system description for the hardware model, and Fig.2 shows how the system self-organizes. First, one of the cells activates itself (we call it the core cell) and send out the sign to connect other cells to three sides 1, 2 and 4 using the connection indicators G_1, G_2 and G_4, and three cells are connected to the core cell. After this process, the conditions $[C_1C_2C_3C_4]$ of the core cell change from [0000] to [1101]. The core cell does not satisfy condition in the first row of the system description, but the forth row and the function F (Fire) is activated. Each cell connected to the core cell satisfies the second, third and fifth row respectively and the function F is activated. Because no row except first row includes function G_i, the organization is completed. This system (robot) moves within an area encircled by a black line (Fig.3). Although all cells of the system are with the same functions and with the same system description, they are specialized: The head of the system acts as a floor sensor, the left and right side cells act as driving wheels.

It is possible to make a lot of kinds of systems (robots) with this system description, such as a system seeking for a light, avoiding a light, avoiding black floor, tracing a black line, etc. There are many systems without any abilities as robots. There can be also case where only one cell is a system (robot). It corresponds to a single cell living thing.

As automatic assembling is difficult in the present level of technology, the cells are assembled by our hand according to the conection indication of the cell shown by LED.

Two examples of systems (robots) are shown in Fig.4 and Fig.5.

TABLE II
AN EXAMPLE OF THE SYSTEM DESCRIPTION OF A HARDWARE MODEL.

S_0	S_1	C_1	C_2	C_3	C_4	N_1	N_2	N_3	N_4	Function
-	-	0	0	0	0	-	-	-	-	G_1 G_2 G_4
-	-	0	1	0	0	-	0	-	-	F
0	-	0	0	1	0	-	-	-	-	F
-	-	1	1	0	1	1	-	-	-	F
-	-	0	0	0	1	-	-	-	-	F

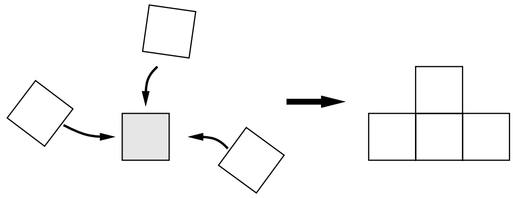


Fig. 2. Self-organization.

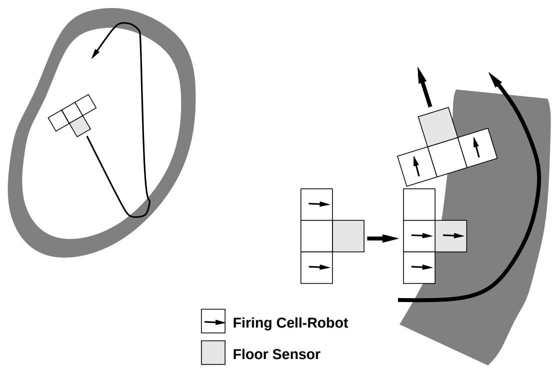


Fig. 3. Behavior of the system (robot).

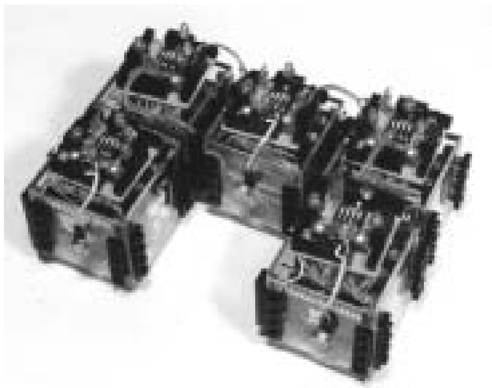


Fig. 4. The system (robot) which traces black line.

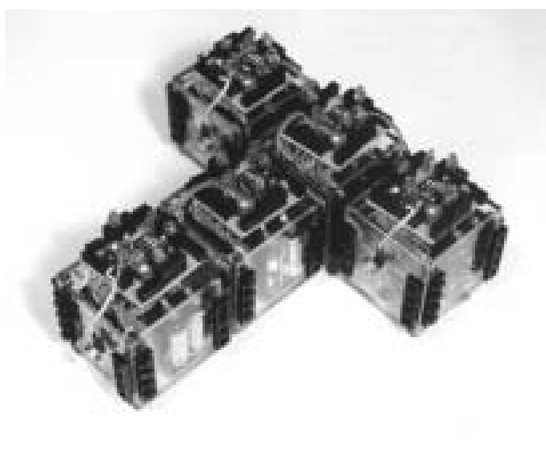


Fig. 5. The system (robot) which moves to a light.

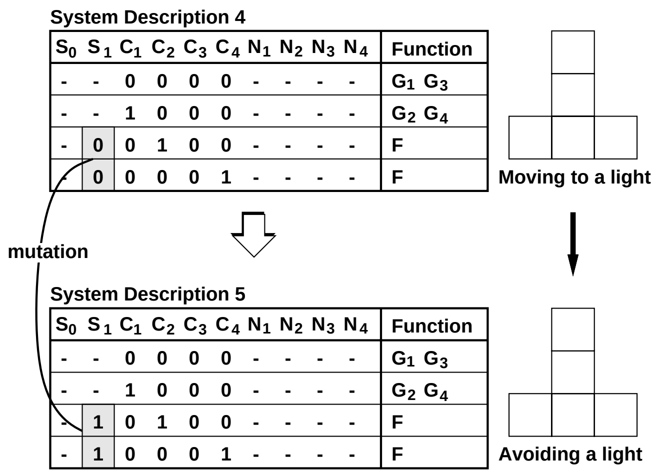
V. Mating and Mutation

Mating and mutations can be applied to the systems (robots). We explain the method for mating with an example. Presume that there are 4 system descriptions (so there are 4 systems). First, two system descriptions are chosen at random, and each system description is cut into two parts randomly, as shown in Fig.7. Next, the top of one system description is connected to the bottom of the other one. Thus, a new system description can be obtained. In Fig.7, as the parent system description 1, which gives the function of moving to a light, and the parent system description 2, which gives the function of avoiding black floor, are mated, the new system description which gives both the function of moving to a light and the function of avoiding black floor are created.

Mutation is applied in the following way. With a given probability, one symbol of the system description is chosen and is changed from 0 to 1 (or 1 to 0). Fig.6 show the example of mutation, where the system description 4, whose specific function is moving to a light, is changed to a new system description, whose specific function is avoiding a light.

Both in mating and in mutations, meaningless (or redundant) parts of the system description (marked with stars in Fig.7) play important roles. See Fig.7 again. In each system description, the parts of the parents system descriptions marked with stars are meaningless, because no cell matches the condition of the rows. However, after these are mated, the meaningless rows are changed to meaningful rows, as the conditions are changed. By repeating mating and mutations, the meaningless rows will appear many times. As the meaningless part turns to "meaningful", both structure and specific function of the system will be changed. It is the meaningless rows that help to create various systems (robots).

DNA also have the meaningless part, which are called *intron* in biology and which are thought to be important for evolution.



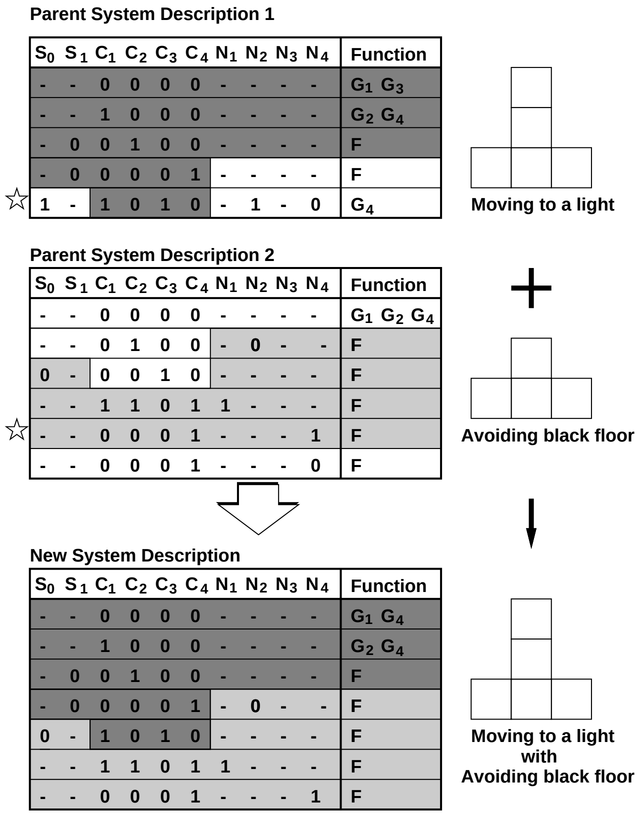
System Description 4

S_0	S_1	C_1	C_2	C_3	C_4	N_1	N_2	N_3	N_4	Function
-	-	0	0	0	0	-	-	-	-	G_1 G_3
-	-	1	0	0	0	-	-	-	-	G_2 G_4
-	0	0	1	0	0	-	-	-	-	F
-	0	0	0	0	1	-	-	-	-	F

System Description 5

S_0	S_1	C_1	C_2	C_3	C_4	N_1	N_2	N_3	N_4	Function
-	-	0	0	0	0	-	-	-	-	G_1 G_3
-	-	1	0	0	0	-	-	-	-	G_2 G_4
-	1	0	1	0	0	-	-	-	-	F
-	1	0	0	0	1	-	-	-	-	F

Fig. 6. Mutation.



Parent System Description 1

	S_0	S_1	C_1	C_2	C_3	C_4	N_1	N_2	N_3	N_4	Function
	-	-	0	0	0	0	-	-	-	-	G_1 G_3
	-	-	1	0	0	0	-	-	-	-	G_2 G_4
	-	0	0	1	0	0	-	-	-	-	F
	-	0	0	0	0	1	-	-	-	-	F
☆	1	-	1	0	1	0	-	1	-	0	G_4

Parent System Description 2

	S_0	S_1	C_1	C_2	C_3	C_4	N_1	N_2	N_3	N_4	Function
	-	-	0	0	0	0	-	-	-	-	G_1 G_2 G_4
	-	-	0	1	0	0	-	0	-	-	F
	0	-	0	0	1	0	-	-	-	-	F
	-	-	1	1	0	1	1	-	-	-	F
☆	-	-	0	0	0	1	-	-	-	1	F
	-	-	0	0	0	1	-	-	-	0	F

New System Description

S_0	S_1	C_1	C_2	C_3	C_4	N_1	N_2	N_3	N_4	Function
-	-	0	0	0	0	-	-	-	-	G_1 G_4
-	-	1	0	0	0	-	-	-	-	G_2 G_4
-	0	0	1	0	0	-	-	-	-	F
-	0	0	0	0	1	-	0	-	-	F
0	-	1	0	1	0	-	-	-	-	F
-	-	1	1	0	1	1	-	-	-	F
-	-	0	0	0	1	-	-	-	1	F

Fig. 7. Mating (Parts marked a star are meaningless).

VI. Computer Simulation for Evolution

A simple computer simulation was done to show that our model of self-organization can be a model of evolution also. There are a few differences between the computer simulation and the hardware model, but the two models are essentially the same. The differences are only conditions and functions of cells.

The following are conditions which cells can give.

Wall sensor:

$$\mathbf{W} = \begin{cases} 0, \text{if the cell is not touching a wall.} \\ 1, \text{if the cell is touching a wall.} \end{cases}$$

Ditch sensor:

$$\mathbf{H} = \begin{cases} 0, \text{if the cell is not in a ditch.} \\ 1, \text{if the cell is in a ditch.} \end{cases}$$

Connection sensors:

$$\mathbf{C_1} \cdots \mathbf{C_4} = \begin{cases} 0, \text{if no cell is connected to side} 1 \cdots 4, \\ \quad \text{respectively.} \\ 1, \text{if a cell is connected to side} 1 \cdots 4, \\ \quad \text{respectively.} \end{cases}$$

The following are functions which cells can execute.

Connection indicator: $\mathbf{G_1} \cdots \mathbf{G_4}$ G_i indicates that a cell should be connected to side i.

Fire F F means that the cell fires.

Direction function: $\uparrow \rightarrow \downarrow \leftarrow$ If a cell fires, the direction to which the system proceeds changes according to direction function.

The index numbers of C_i, N_i and G_i mean directions as the same as the a hardware model.

After a system has self-organized according to the system description, the system is put onto the field shown in Fig.8, where there are ditches, walls and food. The system (robot) which falls into a ditch or comes against a wall is supposed to die. The more food the system gets, the more it adapts to the field (environment) and the more the system is selected as a parent.

Two system descriptions are selected as parents in proportion to how much food they can get, and the system descriptions of the parents are mated into a system description (child). It is permitted that the same systems are selected to be parents. In the computer simulation, the probability that a mutation occurs is 5%, and the population is 50, that is, 50 system descriptions (children) are created from 50 system descriptions (parents). Through generations, the child is expected to obtain abilities of avoiding a ditch and a wall and of getting more food.

The result is shown in Fig.9 and Fig.10. The average score of the systems (50 systems) appeared in each generation is ploted in Fig.9. The score is how much the system can get food before it dies. Fig.10 shows the behavior and structure of three systems (robots) chosen from majority of the systems appeared after 200, 1400 and 1600 generations in the simulation. In Fig.10, the lines with arrows show the behavior of the systems (robots), and the rectangles show the structure of the systems (robots). The number of food gotten by the systems increases through generations, and it can be said that the systems obtained abilities to adapt to environment through mating and mutations.

The system descriptions are not shown here because they are complicated. The mechanism is, however, the same as in the hardware model.

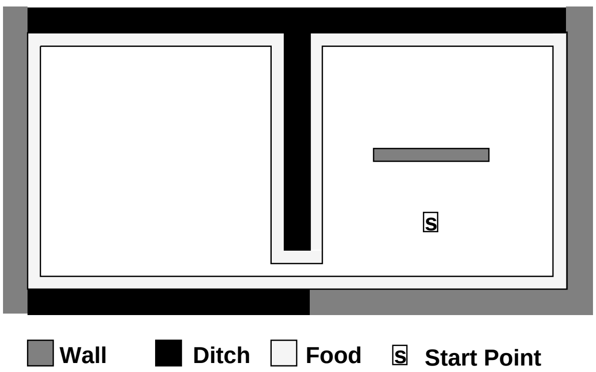


Fig. 8. Field where systems move back and forth.

VII. Conclusions

A model of primitive evolutionary system with the cell-specialization has been constructed, where various systems (robots) are produced automatically from the cells which have the same functions and the system description.

Our experiment of mating and of mutations showed that meaningless parts of system description, which is called *intron* in biology, is important for evolution.

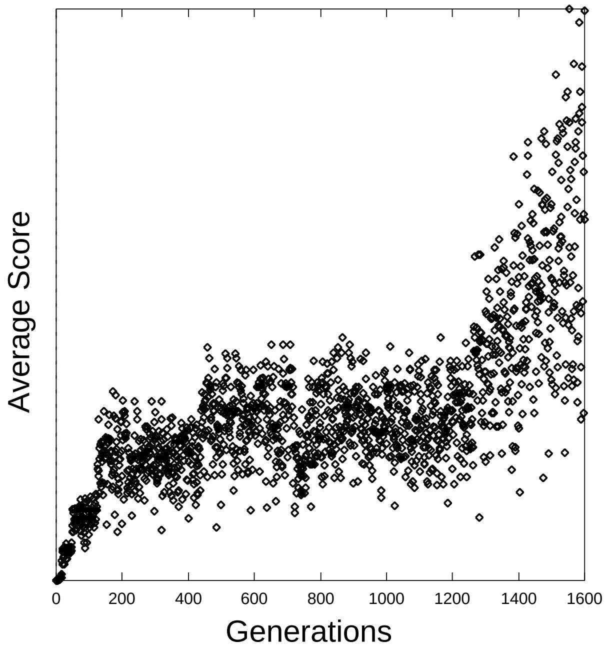


Fig. 9. Result of computer simulation.

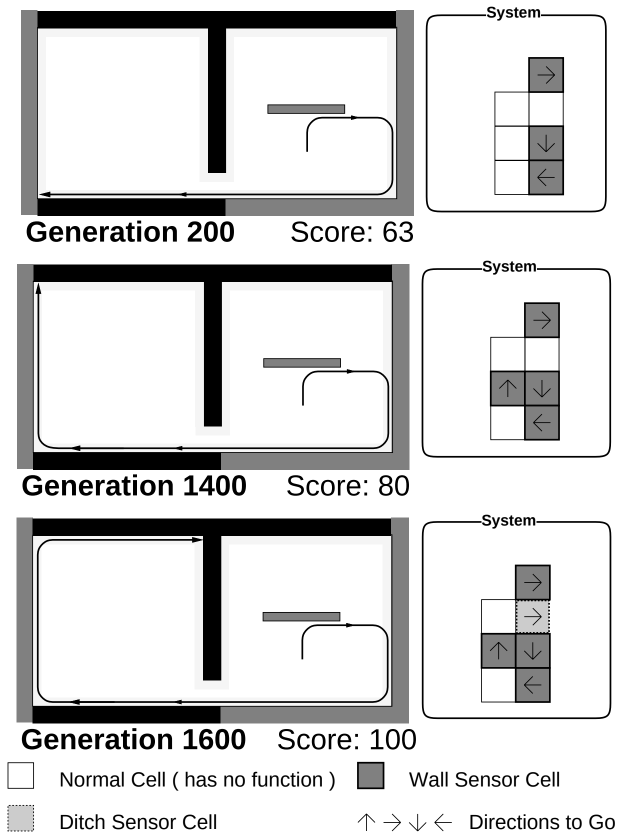


Fig. 10. A typical system (robot) of each generation and its behavior.

We indicate that new systems are created through mating and mutations. And computer simulation showed that the system description is robust for mating and mutations. Our model is considered to show an aspect of evolution in real world.

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