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Structural Organization of Cellular Robot Based on Genetic Information

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Abstract - This paper deals with a structural organization of *Cellular Robotic System* autonomously and distributively as a primitive approach of self-organization. The Cellular Robotic System called *CEBOT* consists of a large number of autonomous robotic units called *cells*. According to the assumption that there are many cells in the environment to configure cellular robots enough, the cells, which have the information of the structure composed by cells, randomly walk to search other cells to configure the structure. Since each cell organizes a cellular module/robot distributively, these cells must coordinate and negotiate to achieve the configuration of a goal structure. In this paper, we consider the behavior of the cells on the basis of the selfish criterion. To evaluate the structural organization as a whole system, we propose the *entropy of structural configuration* as an evaluation criterion for the global system. The simulation represents the influence of the sensing ability of each cell to recognize other cells and the knowledge diffusion for the configuration of the cellular robots.

1. INTRODUCTION

Recently, research works of self-organization have done in several fields attractively. For example, they are (1) the research of the *dissipative structures* by I. Prigogine[Nicolis and Prigogine 1977] in physical chemistry field, (2) the research of the neural networks [Kohonen 1982] and the immunity system [Ishida 1990] in the engineering field, (3) the research of the structure formation in sociology or the dynamics of the population in sociobiology or in the field of artificial life [Hofbauer and Sigmund 1988][Deneubourg, Goss, Frank, Sendova-Franks, Detrain and Chretien 1991], (4) the research of the cell-automaton or the distributed parallel processing in computer science, (5) the research of the synagetics, which includes many fields, by H. Haken [Haken 1983], (6) the research of the self-organizing robotic system with autonomous distributed robots in robotics [Fukuda et al. 1987, 1992][Ueyama, et al. 1992][Hackwood and Beni 1992] and so on.

The capability of self-organization gives the abilities of the self-adaptivity to the environment and the self-evolutionary. The self-organizing system must include the characteristics of an *autonomous distributed system*, an *open system* and, especially in robotic system, a *flexible/reconfigurable structure system.* The system configured by the autonomous distributed system has the abilities of flexibility, responsibility and fault tolerance. Concerning the research of the self-organizing system, we must consider the autonomy, distribution and cooperation in the system.

We have proposed *Cellular Robotic System* called *CEBOT* [Fukuda and Nakagawa 1987] and researched some issues for its realization [Fukuda, et al. 1987, 1992][Ueyama, et al. 1992]. The CEBOT consists of a large number of autonomous robotic units called *cells*. The cell has a simple function. Then the CEBOT is one of the self-organizing robotic system, which has the ability of the dynamic reconfiguration, that is, the self-organization is concerned with both the hardware and the software according to the given tasks or its environments.

The self-organization with interaction among cells. Figure 1 shows the concept of the architecture of the CEBOT as one of the hierarchical self-organizing system. Figure 1 represents the relation between creature and the CEBOT, in which the architecture presents a hierarchy self-organizing structure. In the third layer from the top, cellular module or organ is organized by *cells*. In the fifth layer from the top, cellular robot or individual is organized by the cellular modules or organs. And the CEBOT or society is organized by the cellular robots or the individuals represented in bottom layer.

This paper presents a primitive approach for the self-organization of the structure, which refers to the structural organization of cellular robots. As the primitive approach, we assume that each cell walks randomly yet looking for other cells to organize a desired structure. The sequence of the structural organization progresses according to the connection and separation between cells. As a criterion of the connection and separation behavior, we adopt a selfish criterion to the behavior of the cells. We propose the *entropy of structural configuration* to evaluate the structural organization of a whole system. The simulation results represent the influence of the sensing ability of each cell to recognize other cells and the knowledge diffusion for the configuration of the cellular robots. We also describe the idea of *genetic information*, which presents a structural map such as DNA in biology.

2. DISTRIBUTED STRUCTURE ORGANIZATION

As the state of the structural organization of the CEBOT, (1) the static state and (2) the dynamic state are considered. The static state refers to the condition that the cells and the objects do not move in any term. In the case of the static state, it can configure the structure according to the path planning [Ueyama, et al. 1992]. On the other hand, the dynamic state refers to the condition, in which the cells move independently and moving obstacles exist. In this paper, we consider the dynamic state for the structural configuration of the cellular robots, where each cell randomly walks but without any obstacles in the environment.

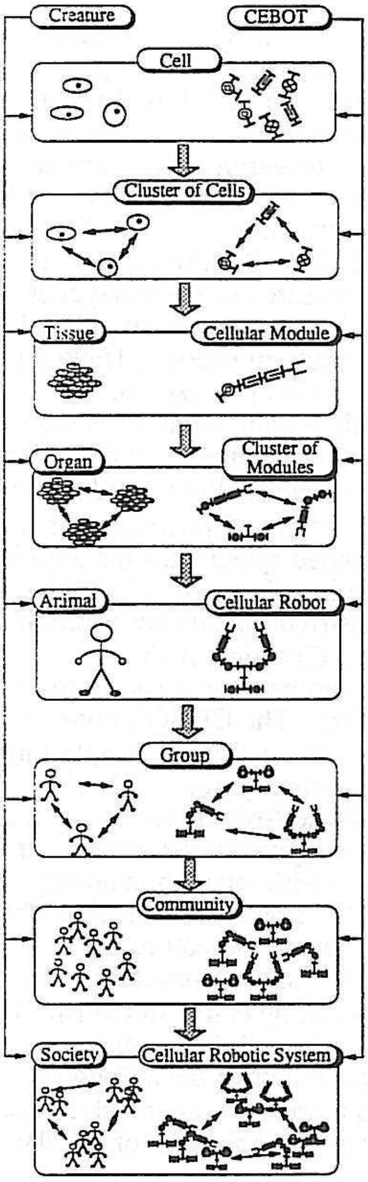

Fig. 1 Relation between creature and CEBOT

To cooperate and coordinate among cells must be considered, since the cells walk randomly, and search other cells to configure cellular robots/modules distributively. The issue of the cooperation among autonomous robots is very important, but it is very difficult to make the rule for the cooperation. In this paper, we adopt a selfish behavior as a behavioral criterion of each cell. In the following chapter, we describe the rule of the behavioral strategy for the cells/cellular modules. Then we define an evaluation function as a criterion for the structural organization of each cellular module and an evaluation function of the whole system including all cells. Here the former evaluation function is used for the behavioral criterion of the connection and separation between cells. Each cell behaves according to the evaluation value independently, so we consider it as selfish behavior. On the other hand, the later evaluation function is used only for the evaluation of the structural organization of the whole system. The later evaluation function is considered as a kind of the entropy, therefor we call it an *entropy of structural configuration.*

3. BEHAVIOR STRATEGY OF CELLS

3.1 Movement of Cell / Cellular Module

The velocity of random walk for a cell or a cellular module is defined as follows:

$$\mathbf{V} = v_m(\mathbf{a} + \mathbf{r}d) \qquad (1)$$

where v_m is a coefficient to consider the movability of the cell or the cellular module, which is given as follows:

$$v_m = v_c \cdot (1 - \log_{10} n / \log_{10} m) \qquad (2)$$

$$if \quad v_m < 2, \quad then \quad v_m = 2,$$

v_c is a constant value. n refers to the number of the cells which compose the cellular module. In the case of a cell, n is 1. m refers to the number of the cells which are included in a reference structure. The reference structure represents an information of the combination of several cells, which is called *genetic information* in this paper. Increasing the number of the cells composing the cellular module, the movability decreases. $\mathbf{a} = (a_x, a_y)$ is a direction vector for the random walk. $|a_x|<1$ and $|a_y|<1$ are generated randomly. $\mathbf{r}d = (r_x, r_y)$ is the vector to consider the distribution of the cells, which for the cell$i$ is given by,

$$r_x = \frac{\sum_{j\in S}(x_j - x_i)}{r_e}, \quad r_y = \frac{\sum_{j\in S}(y_j - y_i)}{r_e}, \quad r_e = \sqrt{\{\sum_{j\in S}(x_j - x_i)\}^2 + \{\sum_{j\in S}(y_j - y_i)\}^2}.$$

S is a set of the cells which are included in the sensing range of the cell$i$. The sensing range presents a area to search other cells or modules to compose the cellular module according to the reference stricture. We assume that the sensing range is limited and each cell can recognize other cells all around in the sensing range. We describe the search method of other cells in the following session.

The cell, as a unit, walks randomly according to the above mentioned method. On the other hand, in addition to the above mentioned method, the cellular module walks randomly according to the following strategy.

(1) Only the cells at the both ends of the module search other cells or modules and behave according to the above described strategy.

(2) The other cells in the module walk randomly without searching other cells, yet considering collision avoidance of the module.

(3) In the sequence of the random walk, one cell determines the direction and distance for random walk and behaves, and the other cells in the module behave such as subordinate cells. The sequence of the random walk is repeated from the cell at the end of the module to the cell at the other end, step by step. The cells, such as subordinate cells, move to the next point according to the velocity determined by the cell, such as master cell in the step, and avoid the collision with other cells or objects without separation from docked cells. To avoid the collision without the separation from docked cells, the cell moves along an adjacent cell.

Figure 2 represents the relation among the structural configuration, sensing ability, and communication.

3.2 Search and Connection of Cells / Cellular Modules

Walking randomly according to the above described strategy, each cell, which exists as a unit, and cellular modules search another cell or module to construct the reference structure. In case of the cellular modules, only the cells at the end of the module search another cell or module and communicate with another cell. The other cells in the module behave such as subordinate cells, when the module walks randomly. The sensing range is limited, and the influence of the limitation is presented in simulation results. When the cell at the end of the module recognizes other cells which are not included in the module, the cell communicates with the nearest cell. Each cell communicates the kind and the state of the cell, where the state refers to the ability of connection with another cell. The kind of the cell and the state of the cell or module must be considered to organize a cellular module according to the reference structure, since the cellular robots consist of several kinds of cells. If the cell dose not have any

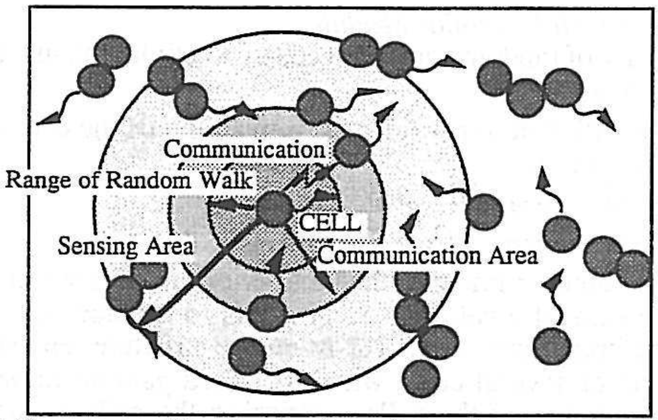

Fig. 2 Relation among the structural configuration, sensing ability, and communication

information concerning the reference structure, the cell behaves such as a resource for the structural configuration. On the other hand, the cell, which has the information about the reference structure, selects a kind of a cell as a candidate of a connection cell based on the comparison between the configuration of the module and the reference structure. As the combinations of the kinds between the cells and the desired cells, we consider three cases, as follows :
(1) the desired cell for one cell is the same kind as the other cell each other,
(2) the desired cell for one cell is not the same kind as the other cell,
(3) the desired cell for one cell is the different kind from the other cell each other.

In the second and third cases, we assume that the cells do not connect each other. In the first case, the cells or modules connect each other. The judgement, connect or not, is performed by the two cells which communicate each other. The judgement is based on only the kind of both the desired cells and the cells, not considered to take account of the structure of the module. In the case of the connection with cellular modules, since the structure of the module is not considered, the organized cellular module will be different from the reference structure, or have a different part to the reference structure in the module. Figure 3 represents an example, in which the incorrect module is organized by the connection between two cellular modules. In this example, the b refers to a bending cell, m refers to a moving cell, and s refers to a sliding cell. In this case, the bending cell at the end of module 1 and the bending cell at the end of module 2 communicate, and both cells must connect with a bending cell, since each cell determines the position of the module at the shading part in the reference structure. As a result of this condition, the cellular modules connect each other. When the incorrect module is organized, the module should separate into two correct modules. In the following section, we describe the idea how to separate the module into two correct modules effectively.

3.3 Separation of Cellular Module

According to the above described reasons, we consider an evaluation criterion to separate the incorrect cellular module into two correct cellular modules. The evaluation criterion is based on the comparison of the configuration between the module and the reference structure. As the criterion, we propose *structural configuration rate* to evaluate the rate of structural organization to the reference structure. The structural configuration rate is defined in the following chapter. Here we assume that each cell can get the information concerning the configuration of the module by using an internal communication bus completely. According to the evaluation function, each cell determines the separation position selfishly, that is, the cells calculate the evaluation value independently and determine whether to connect with adjacent cells or not to obtain the largest value. The behavior is based on the assumption that the connection between cells can be carried out when the both cells tend to connect each other.

In addition to the separation behavior, we assume that the cell at the end of the module separate at any probability, when the cell can not connect with a recognized cell (the cases of (2) and (3) described in section 3.2). In the simulation, we show the

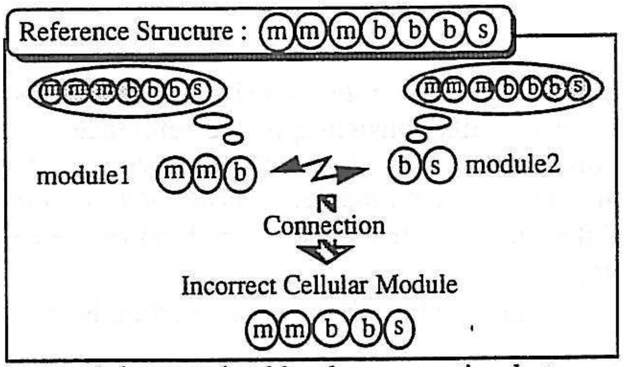

Fig. 3 Incorrect module organized by the connection between two modules

influence of the probability for the structural organization. If we consider the behavior to increase the evaluation value as selfish behavior, the behavior to separate from the module is considered as coordinate behavior, since the separation decreases the evaluation value for the cell which separates from the module.

3.4 Diffusion of Genetic Information

In this paper, the information of the reference structure is given to several cells, which is selected randomly at the initial condition. We assume that the shape of the reference is like string, in which several kinds of cells are included. In this paper, we call the information concerning the reference structure as *genetic information.* The genetic information is copied and reproduced, when the cells or modules connect each other so that each cell evaluate the structural configuration rate to determine the separation or not. The genetic information is transmitted in the module. When the module is separated into two modules according to the above mentioned reasons, the genetic information is diffused in the environment. This diffusion will be effective for the robustness and preservation of the knowledge. In the simulation, we prepare only one kind of the genetic information.

4. EVALUATION OF STRUCTURE CONFIGURATION

In the process of the self-organization by multiple autonomous robots, each autonomous robot must be ordered under the interaction among its environment. In this case, the coordination among the autonomous robots must be required to perform the organization by themselves. As an example of the self-organization with the coordination, we can see the society of human being. Considering that the society is organized by the selfish behavior, which is based on the idea of *selfish gene* by R. Dawkins [Dawkins 1989], we describe the behavior of the cells based on the evaluation function, which is defined in the following section.

4.1 Definition of Evaluation Function

First, the cells, which have the genetic information, determine the position of itself in the reference structure, then the cells search another cells to configure the reference structure with random walk. The genetic information will be considered as a kind of the *positional information* in biology [French, Bryant. and Bryant 1976]. We define the rate of the structural configuration. This function presents how much the structure is organized for each module. Equation (3) presents the *structure configuration rate h(i, t)* as an evaluation criterion for the separation of a cellular module*i*.

$$h(i,t) = \max\left(\frac{\sum_j r_{ij}}{n}\right) \quad \text{where,} \quad r_{ij} = \begin{cases} 1 : same\_kind \\ 0 : nothing \\ -3 : different\_kind \end{cases}, \qquad (3)$$

where, the structure configuration rate $h(i, t)$ is the maximum value of $(\sum_j r_{ij})/n$. ",n" refers to the number of cells consisting of the reference structure. r_{ij} refers to the matching point concerning the kind of a cell between the module and the reference structure at the jth position in the module. r_{ij} is defined as follows :

(1) If the kind of the jth cell is the same as the kind of the cell corresponding to the reference structure, $r_{ij} = 1$.

(2) If there is not a cell at the jth position corresponding to the reference structure, $r_{ij} = 0$.

(3) If the jth cell is the different kind from the cell corresponding to the reference structure, $r_{ij} = -3$.

According to the *genetic information* of the both modules, the structural configuration rates are calculated. By using the value of r_{ij}, in order to obtain the maximum value, the value is calculate for each position. The example is represented in figure 4. In this example, the reference structure is **mmmbbbs**. As a cellular module, the structure **mmbbs** is represented. In the figure, the four cases are represented. For each case, the evaluation value is calculated for each cell (shown in the right column). According to the evaluation function eq.(3), the module is separated into two modules, **mmbb** and s represented in the case (b). Since two moving cells and two bending cells select the case (b), and only one sliding cell selects the case (c), the structure of the case (b) is organized as a results of the selection of each cell.

4.2 Selfish Behavior

In this paper, we define the selfish behavior as a behavior of the cell to obtain the higher value of the structure configuration rate for itself. In the case of the coordination among multiple autonomous robots, it is an important issue how to negotiate among the robots. In this case, it will be more convenient to determine the behavior criterion, where the autonomous robots can achieve the tasks selfishly according to the criterion. But only using the selfish behavior, the solution of the decision making will fall into local minimum, where the local minimum refers to the sub-optimal condition of the decision making. To avoid this condition, it will be necessary to adopt the coordinate behavior by itself. In this paper, if we consider the bahavior to increase the evaluation value as selfish behavior, the behavior to separate from the module will be considered as coordinate behavior, because the separation decreases the evaluation value for the cell which separates from the module.

5. EVALUATION OF GLOBAL ORGANIZATION

In this section, we propose the evaluation function to evaluate the global organization of the system. As the evaluation function for each cellular module, we proposed the structure configuration rate in the above chapter. The global organization of the system refers to the condition of the all cells. The evaluation function for the global organization is only used for the evaluation of the system, not used for the

	Reference Structure : ⓜⓜⓜⓑⓑⓑⓢ	Evaluation values for each cell m - m - b - b - s
(a)	ⓜⓜⓑⓑⓢ	(1, 1, 1, 1, 1)
(b)	ⓜⓜⓑⓑ ⓢ	(4, 4, 4, 4, 1)
(c)	ⓜⓜⓑⓑⓢ	(1, 1, 1, 1, 1)
(d)	ⓜⓜ ⓑⓑⓢ	(2, 2, 3, 3, 3)

Fig. 4 Example of separation between modules

evaluation to configure the cellular modules. The evaluation function *H(t)* as an evaluation function of global organization is defined in the equation (4).

$$H(t)=\sum_{i} h(i,t)\cdot\log_{10}\{\frac{1}{h(i,t)}\} \qquad (4)$$

where *t* refers to the iteration time of random walks, *h(i, t)* refers to the structure configuration rate of the module*i*. From the relation between the equation (4) and the entropy in the information science, we call it the *entropy of the structural configuration*. Here $\sum_{i} h(i,t)\geq 1$.

6. SIMULATIONS

6.1 Assumptions

For the simulation, we have some assumptions, as follows:

(1) As a structure of the cellular robots, we assume one dimensional structure. At the initial condition, the genetic information is given to several cells not all in the system. In the simulation, the cell with a capital letter represents that it has the genetic information and the cell with a small letter represents that it dose not have the information (see Fig. 6).

(2) The space of the environment is 1000 x 700. The diameter of a cell is 20.

(3) We consider three types of cells, moving cell "m," bending cell "b" and sliding cell "s." We assume that each cell walks randomly and the special function of each cell is used for the execution of the task.

(4) We consider that the number of the cells is equal to configure the reference structure, and the number of cells for each type is proportional to the rate of the cells in the reference structure.

(5) We assume that the maximum range of the random walk is 10 which is given at the initial condition.

(6) The cells communicate both the kind of the cell and the condition of the module.

(7) The connector for docking between cells has no polarity and the cell can connect all around the cells.

(8) The genetic information is spread by the copy of the information and separation of the cells.

(9) The sensing range, which is to recognize the cells to communicate and connect with another cell, is 50. On the other hand, we present the influence of the sensing range to recognize the cells, which is used to calculate the direction vector of random walks. And the moving range is 5 to avoid the collision between cells or modules.

6.2 Local Sensing and Knowledge

Figure 5 represents the random walk iteration until the structural organization is performed successfully, corresponding to the sensing area and the number of the cells obtaining the genetic information at the initial condition. But the iteration is limited 500th random walk times. Here the sensing range refers to the radius to recognize other cells to calculate the direction of random walk. The reference structure is given as follows: **m s m s m s m s m s b b b b b.**

In this simulation, we prepared 15 cells in the system, where the number of cells is equal to the number of cells to configure the reference structure. On the other hand, in the case that the number of cells is more than the number of cells to configure the reference structure, we can apply the same strategy to configure the reference structure. In this case, several cellular modules or goal structural cellular robots are produced. The sensing range is from 100 to 500 at an interval of 100. The percentage of the cells obtaining the genetic information at the initial condition is from 20% to 100% at the interval of 20%, where we call the cell obtaining the genetic information as knowledge cell. As we can see from the simulation results, according to the expansion of the sensing range, the random walk iteration decreases to succeed in structural organization. Especially, when the percentage of the knowledge cells is 40%, the structural organization succeeded in the cases of 200 and over sensing range.

Figure 6 shows the state of cells at the initial condition, 200th iteration, and 400th iteration. In the figure 6, the cellular modules are represented as clusters, since the each cell move to avoid the collision along the adjacent cells. The framework of the connection of the module is represented in the figure 6 (c). Figure 7 presents the relation between the entropy values and the random walk iteration, where the sensing ranges are 200 and 400. In the case of 200 sensing range, the complete structure was generated at 386 iteration. In the case of 400, it was generated at 149 iteration. According to the simulation results, the entropy value at the 400 range decreased higher than the entropy value at the 200 range. Because the expansion of the sensing range made the structural organization effective. But in the case of same sensing range, it is not always that the effectiveness of the structural organization depends on the increase of the knowledge cells. It is considered that the increase of the knowledge cells and the expansion of the sensing range occur the incompatibility of decision making of each cell to organize the reference structure.

7. CONCLUSIONS

In this paper, we describe the structural organization of cellular robots based on the primitive approach, which is performed distributively and autonomously. The behavior of the cells depends on the selfish criterion. Under the several assumption, we presented the simulation results and described the influence of the local sensing and the local knowledge called genetic information such as DNA.

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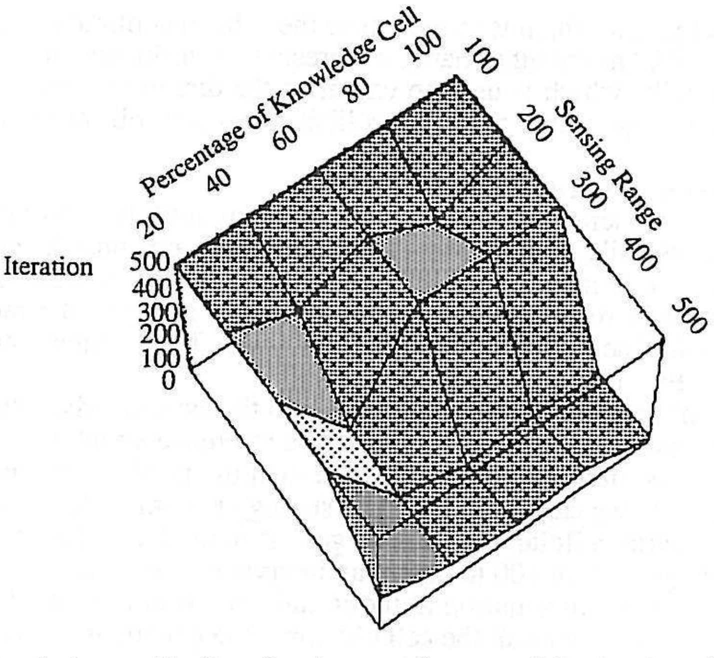

Fig. 5 Relation between the iteration to organize complete structure, local knowledge and local sensing

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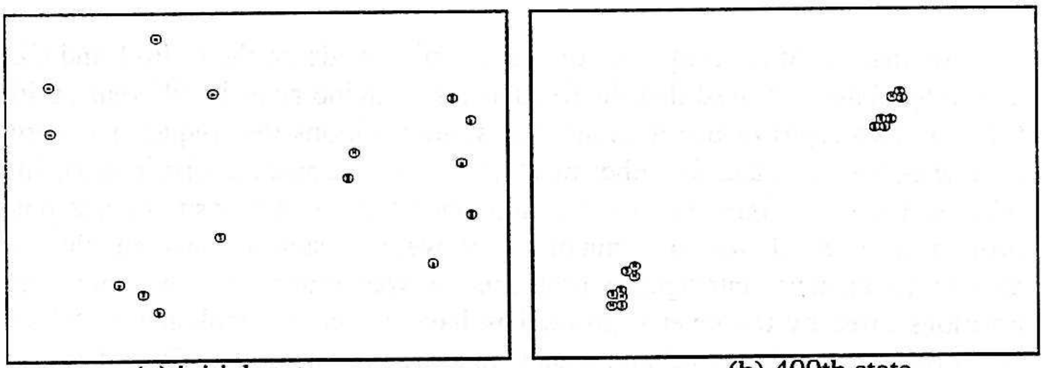
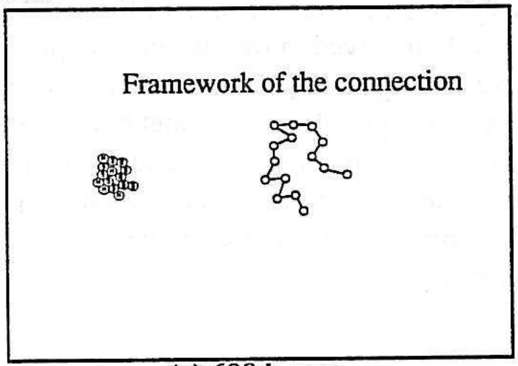


(a) initial state

(b) 400th state



(c) 600th state

Fig. 6 States of cells

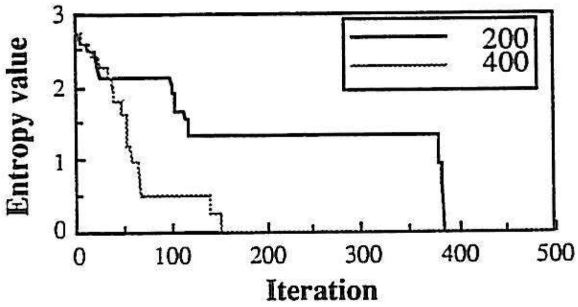


Fig. 7 Relation between the entropy values and iteration of random walk