Task-Oriented Optimal Configuration Structure in a Three-dimensional Self-Organizing Robot by Genetic Algorithms

Kiyotaka Izumi*, Hodaka Tamura** and Keigo Watanabe**
*Department of Mechanical Engineering,
Faculty of Science and Engineering,
**Department of Advanced Systems Control Engineering,
Graduate School of Science and Engineering,
Saga University, 1-Honjomachi, Saga 840-8502, Japan
†E-mail : izumi@me.saga-u.ac.jp

ABSTRACT

This paper describes the construction of a task-oriented configuration structure in the cellular robotic system as a three-dimensional self-organizing robot by using Genetic Algorithms (GAs). To deal with the optimal configuration in three-dimensional environment, a special fitness of GA is introduced: it consists of the reachable height and lifting capacity of the robot. The simulation result shows that the present task-oriented configuration structure method in three dimensional environment can be used to find the desired configuration for a given task.

1. INTRODUCTION

Self-organizing or modular robotic system is an interesting topic. Self-organizing robotic system realizes a useful function by considering a robot as a unit and combining many of them as a robotic system. The robotic system is adaptable and capable of self-organizing and self-evolution; it is just a self-organizing robot system. We call the robot that constructs such a system as a self-organizing robot.

Some self-organizing robots are proposed until now. Fukuda and Nakagawa [1] proposed the dynamically reconfigurable robotic system (DRRS) or the cellular robotic system (CEBOT). The CEBOT consists of several kinds of functional units. Each unit is called a "cell", which possesses at least one function and its own intelligence. Murata *et al.* [2] proposed a "fractum" which can construct a two dimensional robot using magnetic power. TETROBOT [3] system is possible to construct a three-dimensional structure using the concentric multilink spherical (CMS) joint. Pamecha *et al.* [4] has been proposed a metamorphic robotic system using hexagonal modular robots, one of which consists of six links of equal length forming a six bar linkage.

For the dynamic reconfiguration, the method of optimal configuration structure was proposed in the literature for self-organizing robots [1]-[7]. The optimal configuration structure is to structure a configuration from an initial state to a desired state (e.g., optimal configuration). In the conventional approach, it is necessary that the optimal configuration is given to the self-organizing robot. That is, the optimal configuration depending on the desired task must always be given, because of a unique solution in the method. From a practical view point, it is natural to consider a task-oriented configuration structure for self-organizing robot systems. The task-oriented optimal configuration structure of self-organizing robot systems is a method that the self-organizing robot constructs its optimal configuration according to a given task by changing its connection among units.

This paper describes the construction of a task-oriented configuration structure in the cellular robotic system as a three-dimensional self-organizing robot by using Genetic Algorithms (GAs). However, the usual GA coding is not suitable for producing the task-oriented configuration structure. The reason is that any desired configuration in the task-oriented configuration structure is not given by a unique solution; the robot is allowed to find a desired configuration which is available for a given task by learning itself. Therefore, the idea of a binary tree structured GA for the coding is used [7]. To deal with the optimal configuration in three-dimensional environment, a special fitness of GA is introduced: it consists of the reachable height and load capacity of the robot. In addition to the introduced techniques mentioned above, the method of evaluation based on specified units are introduced for GA in order to find a variety of optimal configuration. The simulation result shows that the task-oriented configuration structure method can be used to find a variety of optimal configuration for a given task.

2. CELLULAR ROBOT SYSTEM

The concept of the dynamically reconfigurable robotic system or the cellular robotics was proposed by Fukuda and Nakagawa [1]. In this concept, a robot is constructed by several autonomous functional unit which is called "cell". The robotic system can reconfigure robots in an optimal structure depending on working purposes and environments.

In this paper, we consider the self-organizing robot system based on the cellular robotic system with several modules shown in Fig. 1.

3. TASK-ORIENTED CONFIGURATION USING GENETIC ALGORITHM

Task-oriented Configuration Structure by GA

In the configuration structure method of conventional CEBOT, the desired configuration is prespecified. And in the coding, the used cells are allocated in a line. It is possible to reconstruct the order of combinations among cells used

0-7803-5731-0/99$10.00 ©1999 IEEE

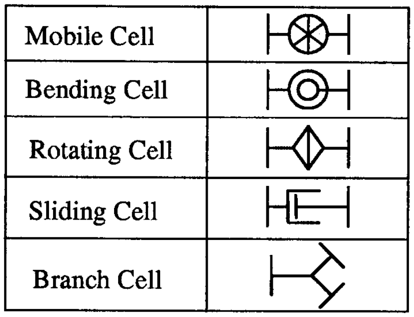


Fig. 1 Modules of the cellular robot system

Table 1 Individual coding with a binary tree structure

Number	1	2	3	4	5
Name	M1	B1	R1	Brl	S1
Left	B1	R1	Brl	S1	B3
Right	*	*	*	B2	*
	6	7	8	9	10
	B2	R2	B3	R3	S2
	R2	S2	R3	*	*
	*	*	*	*	*

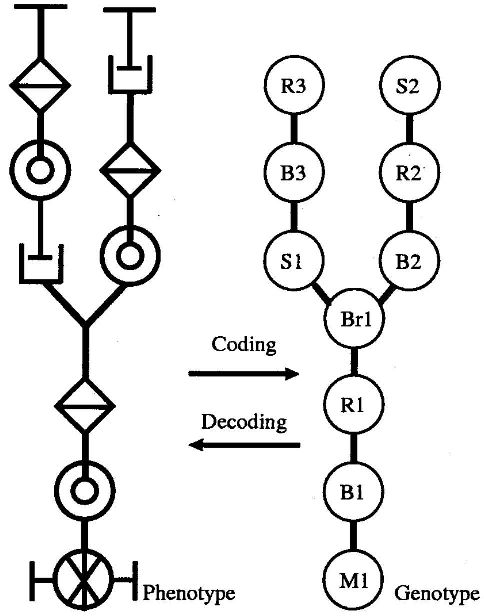


Fig. 2 An example of connection among cells and its coding and decoding

on phenotype by referring the order of gene locus. However, the usual GA coding is not suitable for producing the task-oriented configuration structure. The reason is that any desired configuration in the task-oriented configuration structure is not given by a unique solution; the robot is allowed to find a desired configuration which is available for a given task by learning itself. Therefore, the idea of a binary tree structured GA for the coding is used. The kinds of cells restrict the arrangement of cells. It is supposed that the sufficient number of cells for the configuration structure exists in the environment.

Individual Representation with a Binary Tree Structure

Figure 2 and Table 1 show an example of individual coding with a binary tree structure. In Table 1, the "Number" is the order index number and the "Name" denotes the symbolic representation for a cell on its order. That is, M_i, S_i and R_i are the ith mobile cell, sliding cell and branch cell, respectively, where $i \in \{1, \cdots, 10\}$. B_j is the jth bending cell, where $j \in \{1, \cdots, 30\}$. This symbolic sequence is directly used as a genotype individual. The "Left" and "Right" denote the left and/or right cells connected with the cell represented by "Name", where the concept of "Left" and "Right" are defined toward the starting point cell, the only single right connection is always replaced by the left connection, and $*$ denotes a case when there is no cell.

Genetic Operation of Individual with Three Structure

Crossover and mutation are used for a binary tree structured GA. The crossover is the operation that selects two different individuals from the population and exchanges any cell between two individuals. The mutation is the operation that selects any cell from an individual and exchanges the cell for a cell which has been not used in the individual. Figure 3 shows an example of the genetic operations with a binary tree structure. As a selection method, the combination of roulette selection and elitist preserving strategy is used.

Fitness

In this paper, the task of the cellular robot system is defined that the robot transport the object with mass of 5 [kg] on the ground to the location with 3 [m]. The following assumption is prepared for the task.

1. A moving cell is assumed to exist in an environment, and CEBOT is constructed when the moving cell combines with other cells.
2. An end-effector can hold the object.
3. Length or height of constructed robot is measurable.

At the task setting, an individual is defined as a better one when the moving distance of cells included in the individual is shorter while the cells construct an optimal configuration from an initial configuration, and also when an individual has the configuration such that the cells are able to carry out the task.

Fitness function of n-th individual in a population is described as a combination of the evaluation of moving distance of cells and the rate of task achievement, such as

$$F_n = D_n + T_n, \qquad (1)$$

where, D_n is the evaluation of moving distance such as

$$D_n = e^{-0.01 * d_n}. \qquad (2)$$

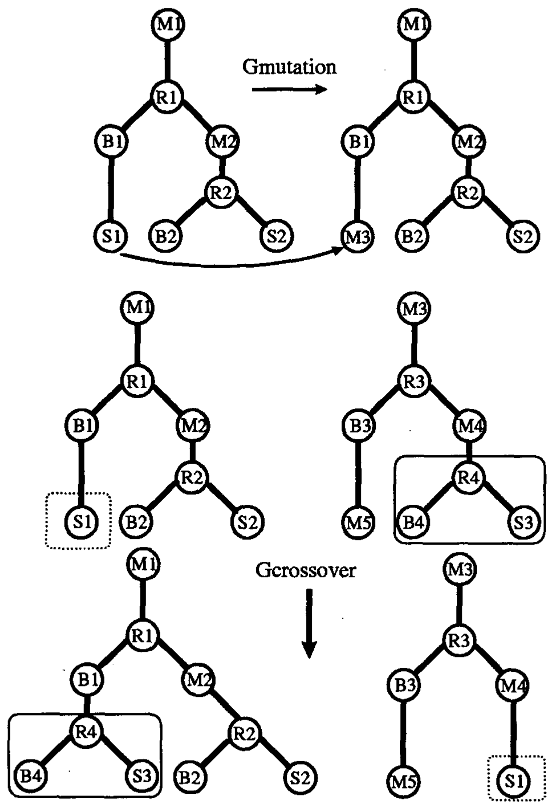


Fig. 3 An example of tree structured GA operation

The moving distance of moving cell is d_n given by

$$d_n = \sum_{k=1}^{end-1} [dis\{Name(k), Name(k+1)\}]. \quad (3)$$

Here end denotes the number of cells used in an individual, $dis\{a,b\}$ denotes the distance from a cell a to a cell b, $Name(k)$ denotes the symbolic representation for the cell that becomes the starting point, $Name(k+1)$ denotes the symbolic representation for the cell that connects with the cell of the starting point.

On the other hand, the rate of task achievement, T_n, is given by

$$T_n = \frac{1}{1+e^{-z_n}} + \frac{1}{1+e^{-p_n}} \quad (4)$$

The evaluation of robot's length is z_n, such as

$$z_n = \max_{i \in M}\{h_i\} - o_{f1}, \quad (5)$$

where the number of terminal cells is M and h_i is the reachable length between i-th terminal cell and ground, and defined by

$$h_i = \sum_{k=1}^{end}[\alpha \, height\{Name(k), Left(k)\} + \beta \, height\{Name(k), right(k)\}]. \quad (6)$$

Table 2 Module specification

Cell type	Length [m]	Lifting capacity [kg]
Mobile	0.5	5.0
Rotating	0.45	8.0
Bending	0.45	8.0
Sliding	0.51	7.0
Branch	0.3	0.5

Table 3 Ability of optimal configuration

Reachable height [m]	Lifting capacity [kg]
4.5	82

Here, the distance between the centers of cells x and y is $height\{x,y\}$, when the relative angle or the length is 0. $Left(k)$ is the cell number in which connects left side with the cell used as a reference point. The cell number in which connects right side is $Right(k)$. If $Left(k)$ is the cell that connects finally with the i-th terminal cell, then $\alpha = 1$ and $\beta = 0$. If $Right(k)$ is the cell that connects finally with the i-th terminal cell, then $\alpha = 0$ and $\beta = 1$.

The evaluation of the load capacity is defined by

$$p_n = \sum_{k=1}^{end} p_{nk} - o_{f2}, \quad (7)$$

where, p_{nk} is the load capacity of cell $Name(k)$ in the n-th individual.

Note that o_{f1} and o_{f2} are offsets in order to limit the values of z_n and p_n between 0 and 1.

4. SIMULATIONS

Parameters of GA were set as follows: the selection was the elite strategy; the rate of crossover was 0.7; the rate of mutation was 0.001. The specification of each module is

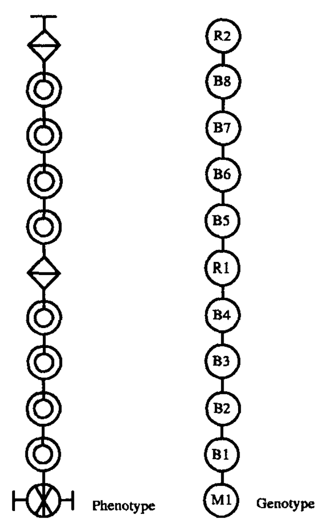


Fig. 4 Optimal configuration for the given task

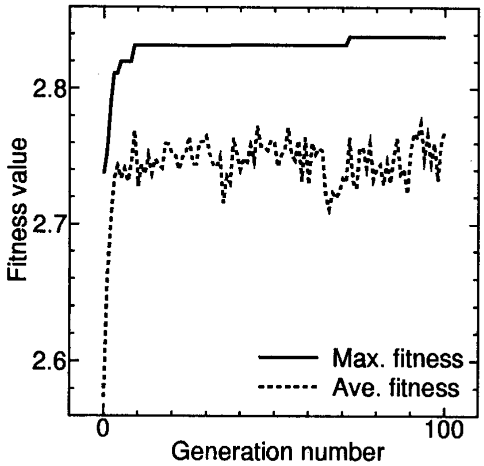
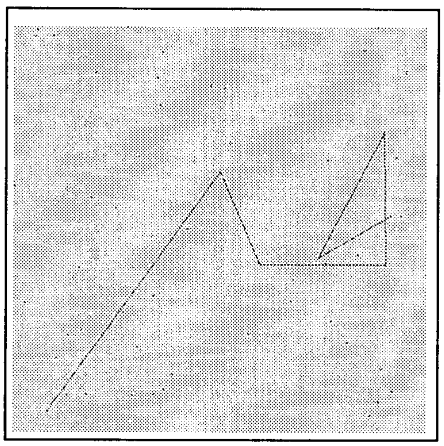


Fig. 5 The fitness history



Generation 0

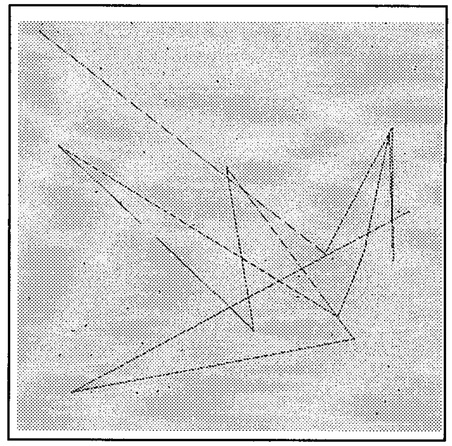
Fig. 6 Moving path at 0th generation

shown in Table 2. Offset values of fitness function are set to be $o_{f1} = 1.5$ and $o_{f2} = 2.5$.

An optimal structure with the maximum fitness at 100th generation is illustrated in Fig. 4. Table 3 shows the capacity of task achievement of the robot with the optimal structure. The history of best fitness value is illustrated in Fig. 5. Paths of the moving cell at 0th, 50th and 100th generation are illustrated in Figs. 6, 7 and 8.

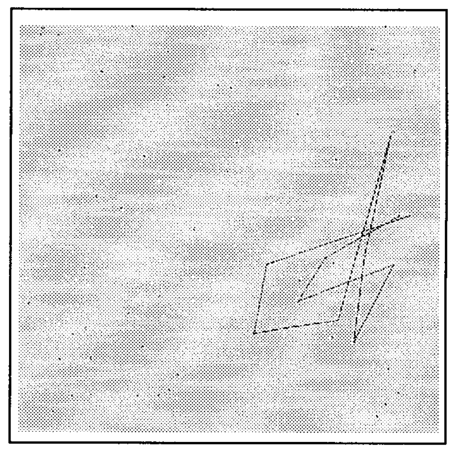
In Fig. 4, the optimal structure is a sirial link without a branch cell. The fitness of a structure with a branch cell is smaller than that of the structure without a branch cell, because the length of the branch cell is shortest among all cells. Thus, it is found that this result is acceptable for the simulation conditions.

The path of the moving cell at 50th generation shown in Fig. 7 is longer than the path at 0th generation shown



Generation 50

Fig. 7 Moving path at 50th generation



Generation 100

Fig. 8 Moving path at 100th generation

in Fig. 6. However, the fitness value at 50th generation is better than that at 0th generation. The optimization problem has two objectives such as the shortest path and the task achievement, thus the result could be obtained, as expected.

Next, the fitness function was modified with weighting parameters such that

$$F_n = \gamma D_n + \delta T_n, \tag{8}$$

where γ is a weighting parameter for an evaluation of moving distance and δ is a weighting parameter for an evaluation of task archivement. The weighting parameters and the simulation results are shown in Table 4. The corresponding configurated results are illustrated in Fig. 9~Fig. 13. In the second and third cases, the fitness function gives a priority to the evaluation of the moving distance over

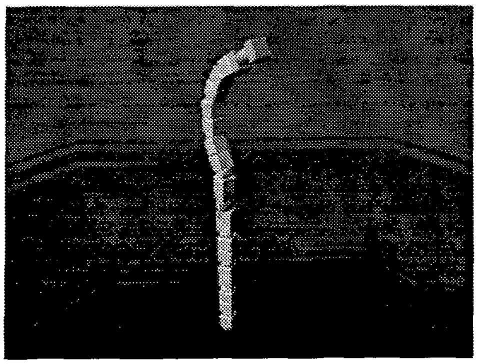


Fig. 9 3D image of optimal configuration for Case 1

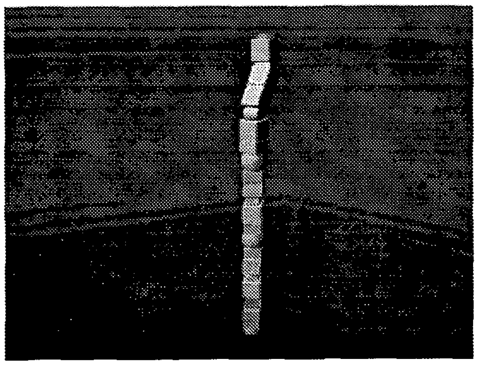


Fig. 10 3D image of optimal configuration for Case 2

the evaluation of the task, so that the total length of the constructed robot becomes shorter than other cases. The shapes of the obtained robots are a serial link type manipulator.

Finally, the task is set so that the robot has six terminal points, and can hold an object, whose mass is 5 [kg]. The evaluation of task achievement is defined as

$$T_n = \frac{R_n}{1+e^{-p_n}} + \frac{1}{1+e^{-b_n}}, \tag{9}$$

where b_n denotes the number of branch cells in the n-th individual, and R_n is the weighting parameter such as

$$R_n = \begin{cases} 10 & p_n \geq 5 \\ 1 & \text{otherwise} . \end{cases} \tag{10}$$

The parameter p_n is the same as in Eq. (4), and the fitness is given by Eq. (1). In order to perform the task, the robot has to contain five branch cells at least. The ability of the configured robot is tabulated in Table 5. It is found form Table 5 that the robot contains five branch cells. The fitness value is illustrated in Fig. 14. The final configuration of the robot is illustrated in Fig. 15.

5. CONCLUSIONS

In this paper, we have proposed a method for optimally constructing a task-oriented cellular robot system by us-

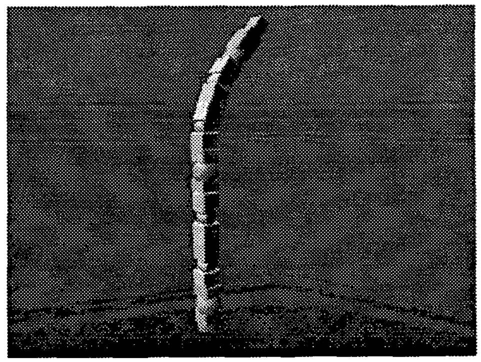


Fig. 11 3D image of optimal configuration for Case 3

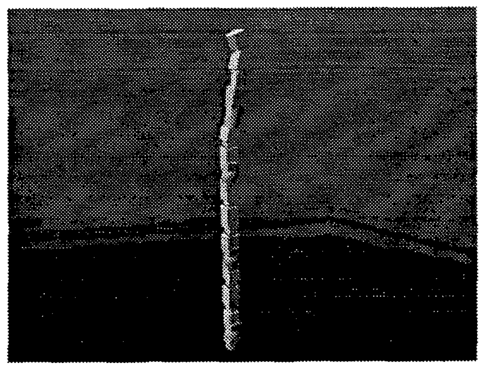


Fig. 12 3D image of optimal configuration for Case 4

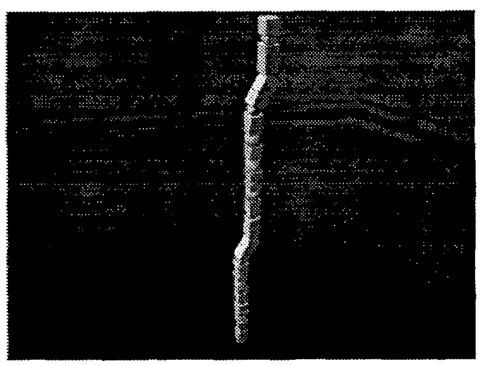


Fig. 13 3D image of optimal configuration for Case 5

Table 4 Simulation results

	γ	δ	Maximum fitness	Average fitness	Hieght	Load Capacity
Case 1	1.0	1.0	2.35	2.26	5.4	98
Case 2	2.0	1.0	3.77	3.68	3.6	65
Case 3	4.0	1.0	5.58	5.39	4.1	70
Case 4	1.0	2.0	4.83	4.76	6.4	104
Case 5	1.0	4.0	8.81	8.70	6.8	116

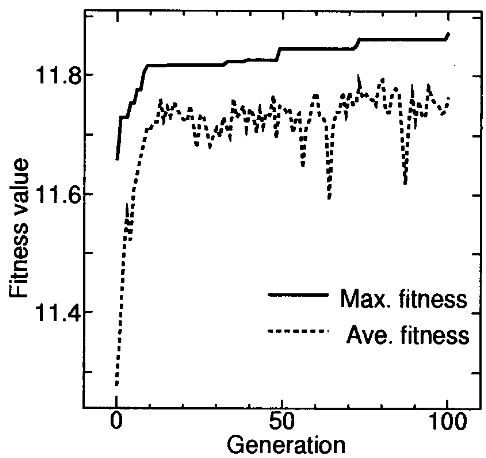


Fig. 14 The fitness history in the new task

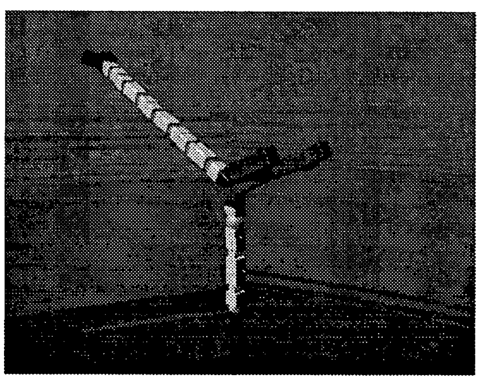


Fig. 15 3D image of optimal configuration for the new task

ing genetic algorithm. The simulation results showed that the tree structured genetic algorithm for the coding could be used to successfully find the desired configuration for a given task in three-dimensional space.

Table 5 Ability of optimal configuration in the new task

Number of branch cell	Load capacity[kg]
5	12

6. REFERENCES

[1] T. Fukuda and S. Nakagawa, "A Dynamically Recongigurable Robotic System (Concept of a System and Optimal Configurations)," *Procs. of IEEE International Conference on Industrial Electronics, Control and Instrumentation*, 1987, pp. 588-595.

[2] S. Murata, H. Kurokawa and S. Kokaji, "Self-assembling Machine," *Procs. of 1994 IEEE International Conference Robotics and Automation*, 1994, pp. 441-448.

[3] G.J. Hamlin and A.C. Sanderson, "Tetrobot: A Modular System for Hyper-Redundant Parallel Robotics," *Procs. of IEEE International Conference on Robotics and Automation*, 1995, pp.863-870.

[4] A. Pamecha, I. Ebert-Uphoff and G.S. Chirikjian, "Useful Metrics for Modular Robot Motion Planning," *IEEE Trans. on Robotics and Automation*, Vol. 13, No. 4, 1997, pp. 531-545.

[5] T. Ueyama, T. Fukuda, F. Arai, T. Sugiura, A. Sakai and T. Uesugi, "A Study on Dynamically Recomfigurable Robotic System (11th Report, Cooperative Generation of Sequence for Structure Configuration using Genetic Algorithm)," *Trans. of the Japan Society of Mechanical Engineers*, Series (C), Vol. 58, No. 554, 1992, pp. 3035-3042 (in Japanese).

[6] K. Izumi, H. Tamura, Y. Ikeda and K. Watanabe, "Initial Configuration Dependence in a Self-Organizing Robot," *Procs. of the Third International Symposium on Artificial Life and Robotics*, Vol. 2, 1998, pp. 510-513.

[7] K. Izumi, H. Tamura, K. Watanabe and K. Sato, "Task-Oriented Optimal Configuration Structure for Cellular Robot Systems," *Procs. of the 4th Japan-France/2nd Asia-Europe Congress on Mechatronics*, Vol. 1, 1998, pp. 322-325.