퍼지 및 지능시스템학회 논문지 2001, Vol. 11, No. 7, pp. 591-597

Cooperative Strategies and Swarm Behavior in Distributed Autonomous Robotic Systems based on Artificial Immune System

Kwee-bo Sim and Dong-wook Lee

School of Electrical and Electronic Engineering, Chung-Ang University
221, Huksuk-Dong, Dongjak-Ku, Seoul 156-756, Korea

Abstract

In this paper, we propose a method of cooperative control (T-cell modeling) and selection of group behavior strategy (B-cell modeling) based on immune system in distributed autonomous robotic systems (DARS). Immune system is living body's self-protection and self-maintenance system. These features can be applied to decision making of optimal swarm behavior in dynamically changing environment. For applying immune system to DARS, a robot is regarded as a B-cell, each environmental condition as an antigen, a behavior strategy as an antibody and control parameter as a T-cell respectively. The executing process of proposed method is as follows. When the environmental condition changes, a robot selects an appropriate behavior strategy. And its behavior strategy is stimulated and suppressed by other robot using communication. Finally much stimulated strategy is adopted as a swarm behavior strategy. This control scheme is based on clonal selection and idiotopic network hypothesis. And it is used for decision making of optimal swarm strategy. By T-cell modeling, adaptation ability of robot is enhanced in dynamic environments.

Key words : Distributed Autonomous Robotic Systems, Artificial Immune System, Group Behavior, Cooperative Control,

1. Introduction

The most significant features of distributed autonomous robotic systems (DARS) are that each robot perceives its environments such as object and the other robot's behavior etc., and they determine their behaviors independently, and cooperate with the other robots in order to perform the given tasks very well [1~4]. DARS has no function to integrate the whole system. But a robot, that is a component of the system, individually understands the objective of the system, environment, behavior of other agents, etc., and decides its behavior autonomously to cooperate with other agent and to establish and maintain order of the whole system. Immune system is also distributed autonomous system that protects and maintains living body [5][6]. The components of immune system do not follow commands of the brain but cope with environment autonomously. In this point of view, we analogize DARS from immune system. So this analogy can be used for mechanism that decides group behavior strategy of DARS.

Immune system has various functions that are ability to recognize foreign pathogens, ability to process information, ability to learn and memorize, ability to discriminate between self and non-self, and ability to keep up harmony of the whole system. It is thought that these functions of immune system can be applied to various engineering fields [7~13].

In this paper, immune system is applied to making action strategy in collective autonomous mobile robots with dynamic environmental changing. In order to improve the adapting ability of robot, we add T-cell model to the immune network equation.

Maniscript received August 1, 2001; revised November 1, 2001. This work was supported by the Braintech 21 from Ministry of Science and Technology of Korea.

2. Biological Immune System

2.1 Concept of Immune System

The protection system that eliminates foreign substances that invade living body is called immune system [8]. The basic components of the immune system are lymphocytes that occur as two major types, B-cells (B lymphocytes) and T-cells (T lymphocytes). B-cells take part in humoral immunity that secretes antibody, and T-cells take part in cell mediated immunity. Each of B-cells has distinct molecular structure and produces 'Y' shaped antibodies from its surfaces. The antibody recognizes antigen that is foreign material and eliminates it. This antigen-antibody relation is innate immune response.

Most antigens have various antigen determinants that are called epitope. In order to grab and latch onto antigen, antibody possesses a structure for the epitope as a key for a lock. This corresponding structure, 'key', is called paratope of the antibody. In addition, recent studies on immunology have clarified that each type of antibody has also its specific antigen determinant called idiotope. So, it is thought that antigen-antibody reaction occurs between antibodies.

2.2 Clonal Selection

Each lymphocyte (whether B-cell or T-cell) is genetically programmed to be capable of recognizing essentially only one particular antigen. The immune system as a whole can specifically recognize many thousands of antigens, so the lymphocyte recognizing any particular antigen must represent only a minute proportion of total. How then is an adequate immune response to an infectious agent generated? The answer is that when an antigen binds to the few cells that can recognize it, they are induced to proliferate rapidly. Within a few days, there are a sufficient number to mount an adequate immune response. In other words, the antigen selects for and generates the specific clones of its own antigen-binding cells, a process called clonal selection. This operates for both B-cells and T-cells.

Lymphocytes that have been stimulated, by binding to their specific antigen, take the first steps towards cell division. They express new receptors that allow them to respond to cytokines from other cells, which signal proliferation. The lymphocyte may also start to secrete cytokines themselves. They will usually go through a number of cycles of division, before differentiating into mature cells, again under the influence of cytokines. For example, proliferating B-cells eventually mature into antibody-producing plasma cells. Even when the infection has been overcome, some of the newly produced lymphocytes remain, available for re-stimulation if the antigen is encountered once more. These cells are called memory cells, since they retain the immunological memory of particular antigen. It is memory cells that confer the lasting immunity to a particular pathogen.

Figure 1 shows the operations of T-cell and B-cell clonal selection, which are basic response of immune system.

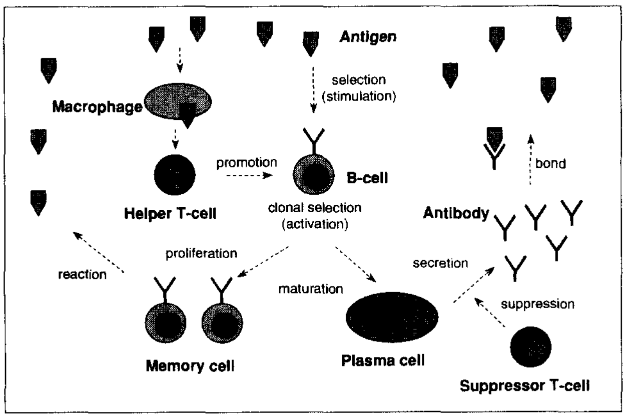


Fig. 1. Operation of T-cell and B-cell clonal selection

2.3 Idiotopic Network

Tolerance to self-antigens is established during ontogeny. However, during the neonatal period the unique binding regions of antigen-specific receptors on B-cell (antibody) and T-cells are present at levels that are too low to generate tolerance. This antigen-specific site is called idiotope. Thus antibodies (B-cells) are stimulated not only antigens but also other antibodies (B-cells). Jerne who is an immunologist proposed idiotopic network hypothesis (immune network hypothesis) based on mutually stimulus and suppression between antibodies [9]. According to this hypothesis, antibodies interact with each other through idiotope and paratope. Such a network relationship plays an important role that needed concentration of antibody keeps up in the immune system. In this way, immune system is parallel-distributed system that operates not unit level but system level.

3. Immune System Modeling

3.1 Immune Network Model of B-cell

Jerne [14] who is an immunologist proposed idiotopic network hypothesis (immune network hypothesis) based on mutually stimulus and suppression between antibodies. Farmer [15] proposed immune network equation (equation (1), (2)) of Jerne's hypothesis. This equation is composed of stimulus and suppression term from antibody, antigen's response term, and cell's natural extinction term.

$$S_i(t) = S_i(t-1) + \left(\alpha \frac{\sum_{j=1}^{N}(m_{ij}s_j(t))}{N} - \alpha \frac{\sum_{k=1}^{N}(m_{ki}s_k(t))}{N} + \beta g_i \right) s_i(t) \qquad (1)$$

$$s_i(t) = \frac{1}{1+\exp(0.5 - S_i(t))} \qquad (2)$$

where $i, j = 0, \cdots, N-1$, N is a number of antibody types, $S_i(t)$ is stimulus value of antibody i, $s_i(t)$ and $s_j(t)$ is concentration of antibodies, m_{ij} is mutual stimulus coefficient of antibody i and j, g_i is affinity of antibody i and antigen, α, β is parameter of response rate at other antibody and antigen, k is natural extinction coefficient.

3.2 Immune Network Model of B-cell and T-cell

In this paper, to improve the adaptation ability of the system, we propose modified immune network equations which is added helper and suppressor T-cell model. Equation (3)~(5) are the modified immune network equations that are modeled on relationship of antigen, B-cell (antibody), and T-cell of immune system.

$$S_i(t) = S_i(t-1) + \left(\alpha \frac{\sum_{j=1}^{N}(m_{ij}s_j(t))}{N} - \alpha \frac{\sum_{k=1}^{N}(m_{ki}s_k(t))}{N} + \beta g_i - c_i(t-1) - k_i \right) s_i(t) \qquad (3)$$

$$s_i(t) = \frac{1}{1+\exp(0.5 - S_i(t))} \quad (4)$$

$$c_i(t) = \eta(1 - g_i(t))S_i(t) \quad (5)$$

where i, j = 0,…,N-1, N is a number of antibody types, $S_i(t)$ is stimulus value of antibody i, $s_i(t)$ is concentration of antibody i, sj(t) is not concentration of self-antibody (Farmer's immune network equation, equation (1), (2)) but that of other robot's antibody obtained by communication, $c_i(t)$ is concentration of T-cell which control concentration of antibody, m_{ij} is mutual stimulus coefficient of antibody i and j, g_i is affinity of antibody i and antigen, α, β, η are constants.

In equation (5), when the stimulus value of antigen ($g_i(t)$) is big and the stimulus value of antibody ($S_i(t)$) is small, the concentration of T-cell ($c_i(t)$) is small. Therefore, in this case ci(t) take a role of helper T-cell that stimulates B-cell. On the contrary, the stimulus value of antigen is small and the stimulus value of antibody is big, the $c_i(t)$ is big. So, it takes part in suppressor T-cell. In biological immune system the helper T-cell activates B-cell when the antigen invades it, and the suppressor T-cell prevents the activation of B-cell when the antigen was eliminated. By adding T-cell modeling, performance of system (making group behavior) is improved.

Table 1. The role of T-cell in different states

gi(t)	Si(t)	ci(t)	state	role of T-cell
big	small	very small	antigen invading	helper T-cell
big	big	small	eliminating	-
small	big	big	eliminated	suppressor T-cell
small	small	small	stable	-

The main reason why the T-cell model was added is that the system adapts the environment quickly by recovery of the concentration of antibody to the initial state when the antigens are removed by antibodies. This is more similar to the biological immune system.

4. Group Control Algorithm Based On Artificial Immune System

Immune system is distributed autonomous system that protects and maintains living body. The components of immune system do not follow commands of the brain but cope with environment autonomously. In this point of view, we analogize DARS from immune system. So this analogy can be used for mechanism that decides group behavior strategy of DARS. Table 2 shows relationship between DARS and immune system.

In this paper, we developed the artificial immune network based control algorithm of group in DARS. In general, the process of DARS to execute the given task is (1) Group behavior(for movement of group or arrangement of the system) → (2) Task execution → (3) Detection of environmental changes → (4) Arbitration of behavior strategies or controlling the group → (1) Group behavior …. In order to achieve this process, we modeled the group behavior and its relation in sec 4.1 and proposed the algorithm for behavior arbitration for group behavior in sec. 4.2.

Table 2. Relationship between DARS and immune system

DARS	Immune System
Robot's environment	Antigen
Action strategy	Antibody
Robot	B-cell
Control parameter	T-cell
Adequacy	Stimulus
Inadequacy	Suppression
Excellent robot	Plasma cell
Inferior robot	Inactivated cell

4.1 Modeling of Group Behavior

Objective of the system and the proposed algorithm

The objective of the system is for robots to find and carry out tasks; the tasks are spread out in the environment. By proposed immune algorithm, strong strategy is selected as a swarm strategy. Namely, all robots select strong strategy. After that, group behavior can be realized. When environmental changes occur, all robots can adapt itself to new situation rapidly. This algorithm is modeled based on clonal selection and immune network hypothesis.

Definition of the antigen

According to the distribution of task, the density of the task is classified into four levels that are ① high, ② medium, ③ low, and ④ nothing. For each of these environments, a robot faces with several strategies that are [1] Aggregation, [2] Random search, [3] Dispersion, and [4] Homing. Accordingly, each environment of four levels is regarded as antigens and each of these strategies is regarded as antibodies.

Definition of the antibody

In this paper, objective of the system is to find and carry out tasks. So in order to find and execute spread tasks, for each environment that is defined above, four strategies are introduced. Each strategy (antibody) and its definition are as follows.

- Aggregation (Ab_0) : the ability of a group of agents to gather in order to establish and maintain some maximum inter-agent distance.
- Random Search (Ab_1 : basic strategy) : the ability to find task by moving random direction.
- Dispersion (Ab_2): the ability of a group of agent to spread out in order to establish and maintain some

minimum inter-agent distance.

- Homing (Ab_3) : the ability to find and go to a particular region or location.

Stimulus value of antigen to antibody is defined as fig. 2, according to the percentage of task detection during past given times (T_c). When density of task is high, stimulus value for aggregation (Ab_0) is also high. Likewise, other functions are defined. Figure 2 represents the definition of every function ($g_0 \sim g_3$) which has overlapping region. Particularly, when the density of the task is zero, g_3 sets as 0.5 and g_2 sets as 0.5. Because of the strategy of g_3 is 'Homing'. Table 3 represents the mutual stimulus coefficient that is the affinity of antibodies in equation (3). Figure 3 shows the conceptual diagram of immune network of equation (3) to (6). This figure represents the interaction between antigens and antibodies (B-cells), antigens and T-cells, and antibodies and antibodies.

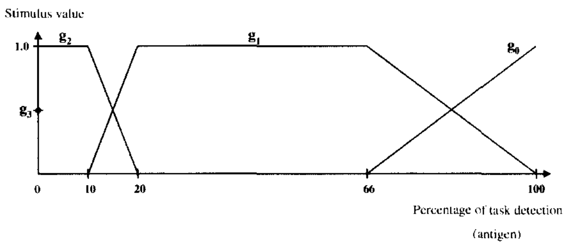


Fig. 2. Stimulus function of antigen to antibody(g_i)

Table 3. Mutual stimulus coefficient(m_{ij})

robot j / robot i	Aggregation (Ab_0)	Search (Ab_1)	Dispersion (Ab_2)	Homing (Ab_3)
Aggregation	1	-0.4	-0.2	-0.4
Search	-0.4	1	-0.4	-0.2
Dispersion	-0.2	-0.4	1	-0.4
Homing	-0.4	-0.2	-0.4	1

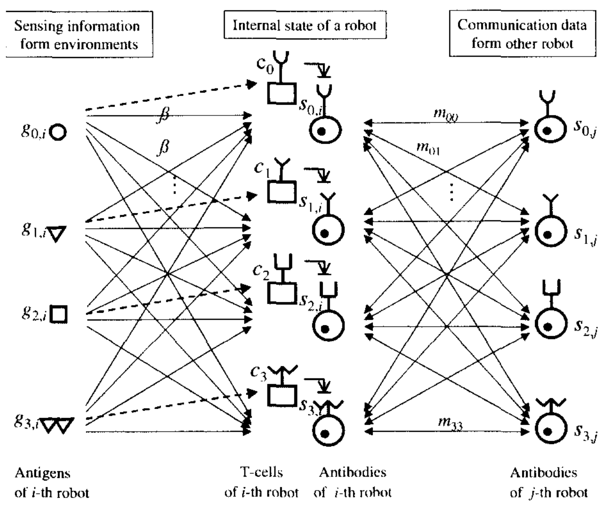


Fig. 3. Proposed immune network include T-cell and B-cell model

4.2 Decision making of Group

When a robot carries out the given task in DARS, the robot must decide its behavior by local information. At this time, the robot is not able to know all the information of the whole system. Thus, it is difficult to realize group behavior such as movement of group or arrangement of system. The idea of the immune response is applicable to arbitration of group strategy in DARS.

Once a robot decides its behavior by perception of its environment, its behavior strategies is stimulated and suppressed by relationship of other robot that encounters. Naturally, this process is accomplished by local communication of autonomous mobile robot. When a robot encounters other robot, if other robot's strategy has the same or similar strategy, this strategy is stimulated, if not, this strategy is suppressed. At this time, if a robot is stimulated very much, its behavior is regarded as adequate one in the system. Therefore, this robot transmits its strategy to other robots. In this way, swarm strategy is decided. Fig. 4 shows conceptual diagram of the process of swarm strategy decision in cooperative search problem.

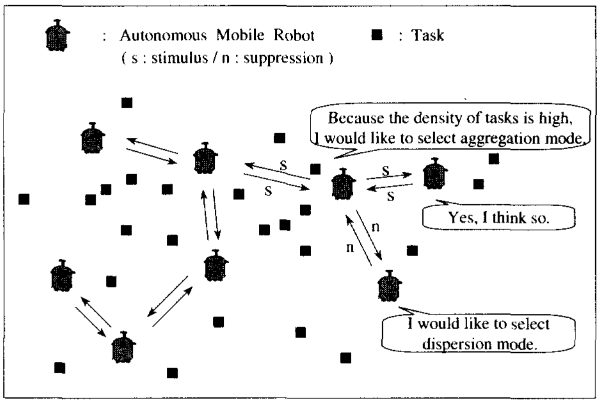


Fig. 4. DARS based on immune system

The detailed algorithm is as follows.

[Step 1]

Initialize stimulus value and concentration of antibody for all action strategies.

$t = 0$

$S_i(0) = s_i(0) = 0.5$ for $i = 0, \cdots, N-1$

where N is the number of action strategies.

[Step 2]

Select and execute strategy (antibody) that has bigger concentration of antibody(s_i) than others(In start, basic strategy(Ab_1) is selected).

[Step 3]

When a robot encounters other robot, they stimulate and suppress each other using local communication. Stimulus value of B-cell(S_i), concentration of antibody(s_i), and concentration of T-cell are calculated by equation (6), (4), and (5) respectively.

The stimulus term and the suppression term are put together as the second term of equation (6), because m_{ij} is plus(stimulus) or minus(suppression) value.

$$S_i(t) = S_i(t-1) + \left(\alpha \frac{\sum_{j=0}^{N-1} m_{ij} s_j(t-1)}{N} + \beta g_i - c_i(t-1) - k_i \right) s_i(t) \quad (6)$$

where i, j = 0,⋯,N-1, s_j is concentration of other robot's antibody, m_{ij} is mutual stimulus coefficient of antibody i and j(table 2), α, β are parameters of response rate of other robots and environment (antigen).

[Step 4]

If a robot has a strategy which was stimulated over upper threshold($\bar{\tau}$), then it becomes excellent robot. → it can transmit strategy to inferior robot when it encounters inferior robot.

If a robot has all strategy which was stimulated under lower threshold($\underline{\tau}$), then it becomes inferior robot.

→ it receives good strategy from excellent robot when it encounters excellent robot.

$$\bar{\tau} \text{ (upper threshold)} = 0.622 (= \frac{1}{1+e^{-0.5}}) \quad (7)$$

$$\underline{\tau} \text{ (lower threshold)} = 0.378 (= \frac{1}{1+e^{0.5}}) \quad (8)$$

[Step 5]

If an inferior robot encounters excellent robot, it receives all strategies and renews concentration of each strategy.

[Step 6]

t = t + 1, go to the Step 2.

Above swarm immune algorithm was modeled on the three parts of immune system that are clonal selection, immune network, and the function of T-cell.

(1) Clonal selection: excellent robot transmits its strategy to others.

(2) Immune network of antibodies (B-cell): Robots stimulate and suppress others by comparison of action strategy using communication.

(3) Helper T-cell and suppressor T-cell: Immune network makes the system identically. Nevertheless, when an environment changes, a robot adapts the environment quickly by recovery of the concentration of antibody to the initial state. This is the function of T-cell.

5. Simulations

The simulation conditions for verifying the effectiveness of the proposed swarm immune algorithm are set as follows.

The fifty robots are spread out in the work space of 10[m]×10[m] wide. The size of robot is 50[mm] in diameter. The objective of system is that robots find and carry out the given tasks, which were spread out in the work area.

We adopt a local communication system in which each robot transmits information locally because it is possible to prevent not only overflow of information but also complexity of communication. In this paper, we use infrared sensor for communication. A robot can transmit information infrared pulses in sequence. In case that each robot face each other, communication between robots are carried out. Each robot diffuses information around with sign-board model. If a robot encounters other robot, these two robots communicate each other. Fig. 5 shows local communication system for autonomous mobile robot. We set a communication radius set as 500[mm] in simulation. Each robot has 12 transmitters and receivers around it at omni-direction. The communication data has robot ID, sensor(transmitter) number, E/I(Excellent or Inferior) robot mode flag and the concentration of four antibodies(fig. 6).

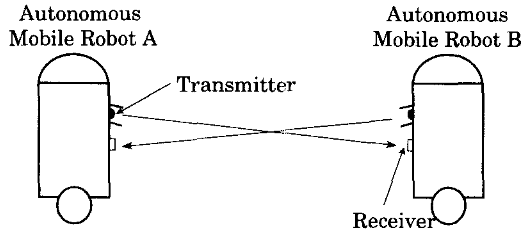


Fig. 5. Local communication system for autonomous mobile robot

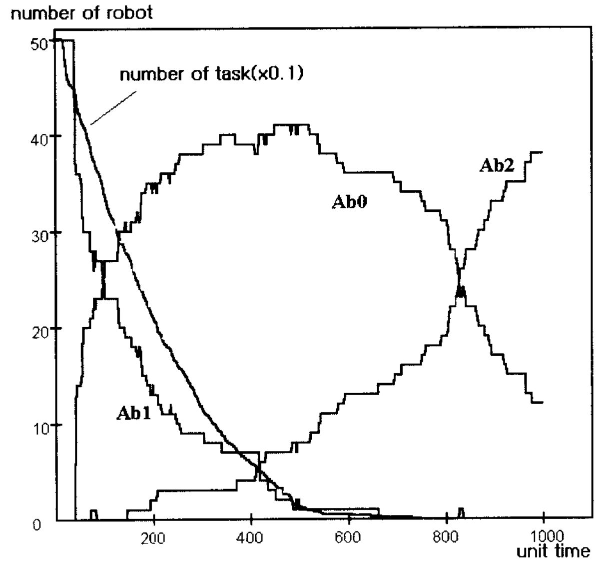
ID	Sensor No.	E/I flag	s_0	s_1	s_2	s_3

Fig. 6 Communication data format

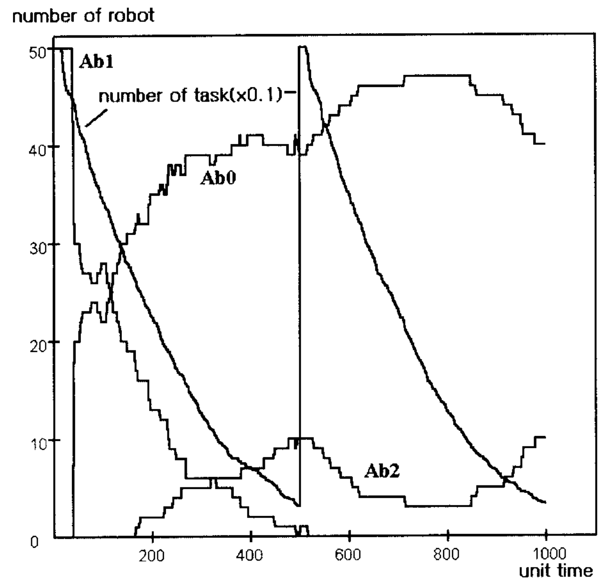
We set the antibody evaluation time(T_c) as 40 unit times to calculate the percentage of task. During 1 unit time, a robot can change its direction or move 25[mm] forward. A robot takes 15 unit times to carry out a task. The number of task is 500. Another simulation parameter values set as α = 0.3, β = 0.05, k = 0.002.

To evaluate the proposed swarm immune algorithm includes B-cell and T-cell modeling and clonal selection, we took the two cases of simulations for verify the effect of T-cell model. **Case 1** is that only using modeling of B-cell and clonal selection. That is equation (6) is not used. **Case 2** is that using modeling of B-cell, T-cell and clonal selection.

Fig. 7 shows the result of the case 1. In fig. 7(a), during from 100 to 200 simulation times, many robots chose the strategy of aggregation, because of the density of task around robot is high. As the simulation time increases, most of robots' strategies are continuous on the aggregation, though the density of task has decreased gradually. In this case, robot's strategy doesn't follow the change of the environments, and the case of fig. 7(b) shows the similar result of it.

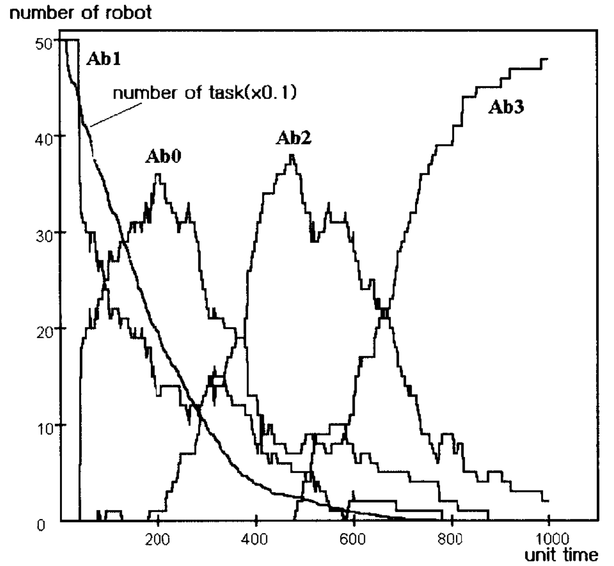


(a) The case that 500 tasks are supplied at 0 unit time

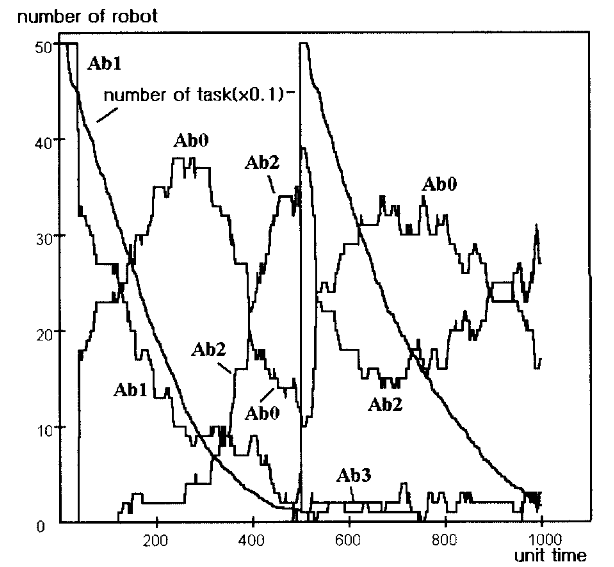


(b) The case that 500 tasks are supplied at 0 and 500 unit time

Fig. 7. Result of using modeling of B-cell and clonal selection



(a) The case that 500 tasks are supplied at 0 unit time



(b) The case that 500 tasks are supplied at 0 and 500 unit time

Fig. 8. Result of using modeling of B-cell, T-cell, and clonal selection

This result shows that B-cell modeling is effective only static environment, because of the lack of adaptation ability. In the biological immune system, the helper T-cell activates B-cell when the antigen invade it, and the suppressor T-cell prevent the activation of B-cell when the antigen was eliminated. Therefore, it is expected that the adaptation ability is enhanced by adding T-cell model.

Fig. 8 shows the result of case 2. In fig. 8(a), during from 100 to 200 simulation times, many robots chose the strategy of aggregation like case 1. However, as the time goes on, the strategy of robot changes to dispersion mode and homing mode. The simulation time reached about 700, robots' strategies change to the strategy of homing. This is the reason why the most tasks are removed. It is similar to the natural immune system that includes T-cells. The adapting ability of proposed immune system improves by using T-cell modeling. Fig. 8(b) is that the tasks are supplied at 500 unit time, in this case, the robots adapt the environment well.

Immune network of B-cell model makes the system identically. Nevertheless, when an environment changes, a robot adapts the environment quickly by recovery of the concentration of antibody to the initial state. Therefore, as the number of task is decrease, the group behavior is emerged following order; (1) random search (2) aggregation (3) dispersion (4) homing.

6. Conclusion

This paper proposed the algorithm based on immune system to achieve the goal of DARS. We found the analogy between DARS and immune system, and applied to making swarm strategy in DARS. We made a condition that swarm behavior emerged, it could be achieved only when a successful strategies are selected by all robots in the system. This is based on clonal selection that a successful clone is selected and proliferated, and immune network hypothesis that is modeled after mutual action of antibodies. In order to improve the adapting ability of robot in changing environment, we proposed the T-cell model of the immune network equation.

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Kwee-Bo Sim

Kwee-Bo Sim was born September 20. 1956. He received the B.S. and M.S. degrees in Department of Electronic Engineering from Chung-Ang University, Seoul Korea, in 1984 and 1986 respectively, and Ph. D. degree in Department of Electronic Engineering from the University of Tokyo, japan, in 1990. Since 1991, he has been a faculty member of the School of Electrical and Electronic Engineering at the Chung-Ang University, where he is currently a Professor. His research interests are Artificial Life, Neuro-Fuzzy and Soft Computing, Evolutionary Computation, Learning and Adaptation Algorithm, Autonomous Decentralized System, Intelligent Control and Robot System, and Artificial Immune System etc. He is a member of IEEE, SICE, RSJ, KITE, KIEE, ICASE, and KFIS.

Phone : +82-2-820-5319
Fax : +82-2-817-0553
E-mail : kbsim@cau.ac.kr

Dong-Wook Lee

Dong-wook Lee was born August 24, 1973. He received the B.S. M.S., and Ph.. D degree in Department of Control and Instrumentation Engineering from Chung-Ang University, Seoul, Korea, in 1996. 1998, and 2000 respectively. His research interests are Evolutionary Computation, Artificial Life, Artificial Immune System, and Evolvable Hardware. He is a member of KITE, KIEE, ICASE, and KFIS.

Phone : +82-2-820-5319
Fax : +82-2-817-0553
E-mail : dwlee@ms.cau.ac.kr