Decentralized Consensus-making Mechanisms Based on Immune System

~Application to a Behavior Arbitration of an Autonomous Mobile Robot~

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Abstract— **Conventional artificial intelligent (AI) system have been criticized for its brittleness under hostile /dynamic changing environments. Therefore, recently much attention has been focused on the reactive planning systems such as behavior-based AI. However, in the behavior-based AI approaches, how to construct a mechanism that realizes adequate arbitration among competence modules is still an open question. In this paper, we propose a new decentralized consensus-making system inspired from the biological immune system. And we apply our proposed method to a behavior arbitration of an autonomous mobile robot as a practical example. To verify the feasibility of our method, we carry out some experiments. In addition, we propose an adaptation mechanism, and try to construct a suitable immune network for adequate action selection.**

I. Introduction

In recent years much attention has been focused on *behavior-based artificial intelligence(AI)*, which have already been demonstrated its robustness and flexibility against dynamically changing world. However, in this approach, how to construct a mechanism that adequately arbitrates multiple competence modules (i.e. simple behavior/action) is still an open question *Brooks* showed a solution to this problem with use of *subsumption architecture*[1; 2]. Although this method demonstrates highly robustness, it should be noted that this architecture arbitrates the prepared competence modules on a fixed priority basis. It would be quite natural to vary the priorities of the prepared competence modules according to the situation. *Maes* proposed an another flexible mechanism called *behavior network system*[3; 4]. In this method, agents form a network based on cause-effect relationship, and an agent suitable for the current situation and the given goals emerges as the result of activation propagation among agents. This method, however, difficult to apply to a problem where it is hard to find our cause-effect relationship among agents.

On the other hand, the immune system has various interesting features such as immunological memory, immunological tolerance, pattern recognition, and so on viewed from the engineering standpoint. Recent studies on immunology have clarified that the immune system does not just detect and eliminate the non-self materials called *antigen* such as virus, cancer cells and so on, rather plays important roles to maintain its own system against dynamically changing environments through the interaction among lymphocytes/antibodies. Therefore, the immune system would be expected to provide a new methodology suitable for dynamic problems dealing with unknown/hostile environments rather than static problems.

Based on the above facts, we have been trying to engineer methods of the immune system and apply to robotics and so on [5; 6; 7]. We expect that there would be an interesting AI technique suitable for dynamically changing environment by imitating the immune system in living organisms. In this paper, we propose a new decentralized consensus-making system inspired from the biological immune system. We then apply to a behavior arbitration of an autonomous mobile robots as a practical example. In order to verify the validity of our proposed method, we perform some experiments. In addition, we try to evolve the proposed artificial immune network using reinforcement signals. Finally, we show an another evolutionary mechanism from the selectionist standpoint.

II. Overview of biological immune system

The basic components of the immune system are *lymphocytes* that are mainly classified into two types: *B-lymphocytes* and *T-lymphocytes*. B-lymphocytes are the cells produced from *bone marrow*. Roughly 10^7 distinct types of B-lymphocytes are contained in a human body, each of which has distinct molecular structure and produces "Y" shaped *antibodies* from its surfaces. The antibody recognizes its specific *antigens*, which are foreign substance that invade living creature. This reaction is often likened to *a lock and key relationship* (see Fig.1). To cope with continuously changing environment, living systems possess enormous repertoire of antibodies in advance. On the other hand, T-lymphocytes are the cells produced from *thymus*, and they generally perform to regulate the production of antibodies from B-lymphocytes as outside circuits of B-lymphocyte network (idiotypic network) discussed later.

For the sake of convenience in the following explanation, we furthermore introduce several terminology in immunology. The portion on the antigen recognized by the antibody is called *epitope* (antigen determinant), and the one on the antibody that recognizes the corresponding antigen determinant is called *paratope*. Recent studies on immunology have clarified that each type of antibody also has its specific antigen determinant called *idiotope* (see Fig.1).

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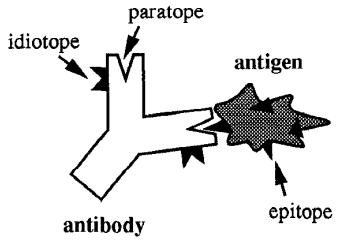


Fig. 1. Structure of an antigen and an antibody.

Based on this fact, *N.K.Jerne*, an immunologist, proposed a remarkable hypothesis which he has called the *"idiotypic network hypothesis"*, sometimes called "immune network hypothesis" [8; 9; 10; 11; 12]. This network hypothesis is the concept that antibodies/lymphocytes are not just isolated, namely they are communicating to each other among different species of antibodies/lymphocytes. This idea of *Jerne's* is schematically shown in Fig.2. As shown in the figure, the stimulation and suppression chains among antibodies form a large-scaled network and works as a self and non-self recognizer. Therefore, the immune system would provide a new parallel distributed processing architecture.

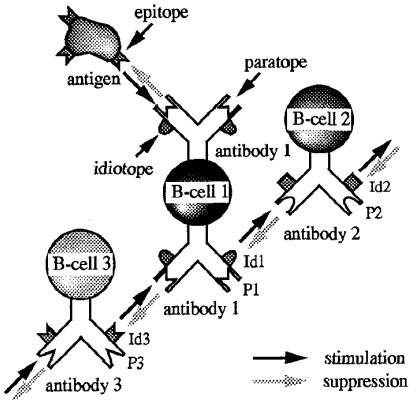
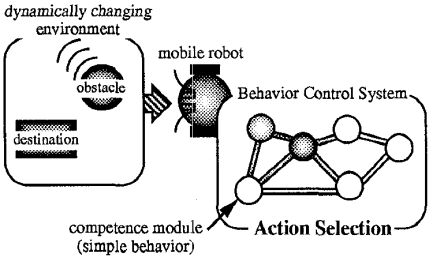


Fig. 2. Jerne's idiotypic networks hypothesis.

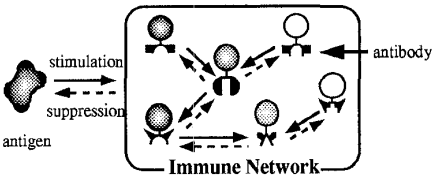
III. Proposed Consensus-making Network Based on Biological Immune System

A. Action selection and Immune system

As described earlier, in the behavior-based AI, how to construct a mechanism that realizes adequate arbitration among the prepared competence modules is still an open question. To overcome this problem, several methods have been proposed[1; 2; 3; 4]. Against the above-mentioned stream of works, we approach to this problem from the immunological standpoint, more concretely with use of immune network architecture. Fig.3 schematically illustrates the action selection system for an autonomous mobile robot and the immune network architecture. As shown in this figure, current situations, for example, distance and direction to the obstacle detected by the installed sensors work as antigens, and a prepared competence module (simple behavior) can be regarded as an antibody (or B-lymphocyte), while the interaction between modules is represented by stimulation and suppression between antibodies. The basic concept of our method is that the immune system equipped with the autonomous mobile robot selects a competence module (antibody) suitable for the detected current situation (antigen) in a bottom-up manner.



(a) An autonomous mobile robot with an action selection mechanism.



(b) Immune network.

Fig. 3. Basic concept of our proposed method.

B. Problem

For the ease of the following explanation, we firstly describe the experimental setup used to confirm the ability of an autonomous mobile robot with our proposed immune network-based action selection mechanism (for convenience, dubbed *"immunoid"*). Fig.4 shows the experimental setup. The arena is surrounded by white polystyrene walls (approximately 50cm x 50cm), and contains the following two kinds of objects: 1) *multiple obstacles*(movable) and 2) *one charging station.* As seen in the figure, the charging station is represented by an electric-light bulb. And we assume that prespecified quantity of initial energy is given to the immunoid at the beginning of each trial, and the current energy level can be detected by the simulated internal sensor installed in the immunoid. For quantitative evaluation, we use the following assumptions:

1. if the immunoid moves, it consumes energy due to the metabolism.
2. if the immunoid collides with an obstacle, it loses some energy.
3. if the immunoid reaches the charging station, it instantaneously obtains full energy. However,

if the energy level of the immunoid is high, `go_to_charging_station` behavior might not emerge to avoid over-charging.

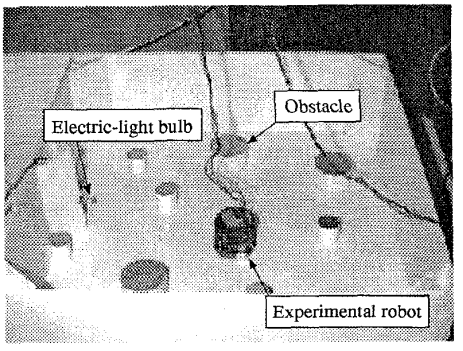


Fig. 4. Experimental setup.

Fig.5 indicates the structure of the immunoid used in the experiments. As illustrated in the figure, the immunoid has eight infrared(IR) proximity sensors, one image sensor and one simulated energy level detector. Each IR sensor can detect the existence of obstacles within approximately 3cm. On the other hand, the image sensor can recognize the direction of the charging station within 36 degrees in the front. For simplicity, we categorize the eight IR sensors into the following four group: *front, right, left* and *back*. And we prepare ten kinds of simple behaviors for the immunoid: *move forward (default), avoid obstacle (move forward, move backward, turn right, turn left), go to charging station (move forward, turn right, turn left), search for charging station (turn right, turn left)*. The aim of the immunoid is to survive as long as possible. To realize this aim, the immunoid must go to the charging station regularly in order to fill up energy level without collisions. To do so, the immunoid must select an action (antibody) suitable for the current detected situation (antigen).

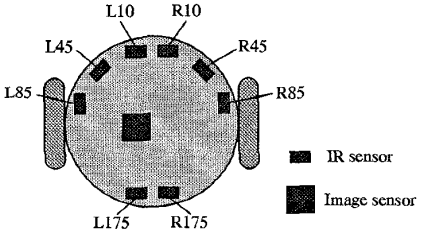


Fig. 5. Structure of the immunoid.

C. Definition of the antigens and antibodies

As described earlier, the detected current situation and prepared simple behavior work as an antigen and an antibody, respectively. In this study, each antigen informs the existence of obstacle and/or charging station or current energy level. Based on this, we describe the detected antigen in the following manner: *object* (i.e. obstacle or charging station)—*direction* (i.e. front, right, left, back (only obstacle), none), or *current energy level—state* (high, low). Note that the concentration of the antigen concerned with the current energy level is varied according to the remaining energy quantity, while those of another antigens are constant.

Next, we explain how we describe an antibody in detail. To make the immunoid select a suitable antibody against the current antigen, we must look carefully into the definition of the antibodies. Moreover, we should notice that our immunological arbitration mechanism selects an antibody in a bottom-up manner by interacting among antibodies. To realize the above requirements, we defined the description of antibodies as follows. As mentioned in the previous section, the identity of each antibody is generally determined by the structure (e.g. molecular shape) of its paratope and idiotope. Fig.6 depicts our proposed definition of antibodies. As depicted in the figure, we assign a pair of desirable condition and the corresponding action to the paratope, and the ID–number of the disallowed antibodies and their degrees of disallowance to the idiotope, respectively. The structure of the desirable condition is the same as the antigen described above.

In addition, for the adequate selection of antibodies, we assign one state variable called *concentration* to each antibody.

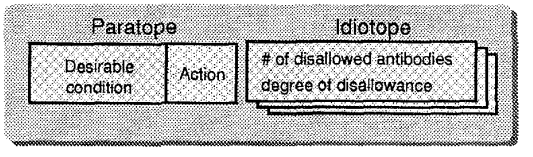


Fig. 6. Definition of antibody.

D. Interaction between antibodies

Next, we explain the interaction between antibodies ,that is, the basic principle of our immunological consensus-making networks in detail.

For the ease of understanding, we assume that the immunoid is placed in the situation shown in Fig.7 as an example. In this situation, three antigens listed in the same figure invade into the immunoid's interior. Suppose that the listed four antibodies are prepared in advance that respond to these antigens. For example, antibody 1 means that if the immunoid detects the charging station in the right direction, this antibody can be activated and would cause `turn_right` action. However, if the current energy level is high, this antibody would give way to other antibodies represented by its idiotope (in this case, antibody 4) to prevent over-charging.

Now assume that the antigen concerned with energy level low does not exist (i.e. immunoid has enough energy), antibodies 1, 2 and 4 are stimulated by the antigens. As a result, the concentration of these antibodies increases. However, there are interactions indicated by arrows among

the antibodies through their paratopes and idiotopes. Consequently, the concentration of each antibody varies. Finally, antibody 2 will have the highest concentration, and then permitted to be activated.

In the case the immunoid has not enough energy, antibody 1 tends to be selected in the same way.

As observed in this example, the interactions among the antibodies work as a priority adjustment mechanism.

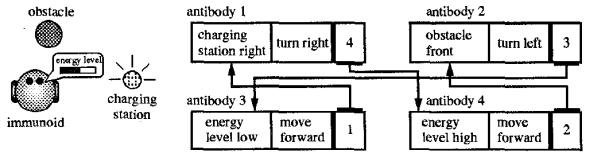


Fig. 7. An example of consensus-making network by interacting among antibodies.

E. Dynamics

The concentration of i-th antibody, which is denoted by a_i, is calculated as follows:

$$\frac{dA_i(t)}{dt} = \left(\sum_{j=1}^{N} m_{ji} a_j(t) - \sum_{k=1}^{N} m_{ik} a_k(t) + m_i - k_i \right) a_i(t) \tag{1}$$

$$a_i(t+1) = \frac{1}{1 + \exp(0.5 - A_i(t))} \quad , \tag{2}$$

where, in equation (1), N is the number of antibodies. m_{ji} and m_i denote affinities between antibody j and antibody i (i.e. the degree of disallowance), and antibody i and the detected antigen, respectively. The first and second terms of the right hand side denote the stimulation and suppression from other antibodies, respectively. The third term represents the stimulation from the antigen, and the forth term the dissipation factor (i.e. *natural death*). Equation (2) is a squashing function used to ensure the stability of the concentration. In this study, selection of antibodies is simply carried out in a *winner-take-all* fashion. Namely, only one antibody is allowed to activate and act its corresponding behavior to the world if its concentration surpasses the prespecified threshold.

F. Results

To verify the feasibility of our proposed method, we carried out some experiments. As a rudimentary stage of investigation, we prepared 18 antibodies of which paratope and idiotope are described a priori (Fig.8). In the figure, note that the degrees of disallowances are omitted in each idiotope for lack of space. At the beginning of the experiments, we equipped the immunoid with the maximum energy level (i.e. 200). Obtained results are as follows: while the energy level is enough, the immunoid moves around the arena avoiding obstacles. As the remaining energy runs out, the immunoid tends to select an antibodies concerned with `go_to_charging_station` and/or `search_for_charging_station` behaviors. After successful reaching the station, the immunoid starts to move around again. Such a regular behavior could be frequently observed in the experiments.

In order to evaluate the arbitration ability of our proposed mechanism, we furthermore carried out simple experiments by varying the remaining energy level. Fig.9(a) depicts the initial position of the immunoid. As shown in the figure, in this situation, both the obstacles and the charging station exist in the front of the immunoid. Fig.9(b), (c) and (d) are the resultant trajectories of the immunoid in the case where the initial energy level is set to 200 (maximum), 100 and 50, respectively. In case 1, it can been seen that the immunoid mainly pays attention to avoiding obstacles since the concentration of the antigen concerned with energy level high is higher than that of energy level low. In case 2, since the the concentration of the antigen concerned with energy level high is almost equal to that of energy level low, the immunoid firstly tries to avoid obstacles and then shifts to `go_to_charging_station` behavior. In case 3, due to the critical energy level, the immunoid thrusts its way through the obstacles and goes straight to the charging station. From these results, in spite of the simple experiments, it is understood that the immunoid selects an action (antibody) according to the current situation (antigen) by flexibly changing the priorities of the prepared competence modules.

IV. Adaptation Mechanisms

For more usefulness, as some researchers have been pointed out, the introduction of some adaptation mechanisms is highly indispensable. Adaptation mechanism is usually classified into two types: *adjustment* and *innovation* [13; 14]. In the followings, we propose an adjustment mechanism suitable for the proposed system, and show a possible/promising innovation mechanism.

A. Adjustment mechanism

For an adequate consensus-making, it is necessary to appropriately determine the disallowed antibody and its degree of disallowance m_{ij}, i.e. priorities among antibodies. To realize this aim, we propose an on-line adaptation mechanism using the advantages of the prementioned description of antibodies. Additionally, it is desired that this mechanism can even work under the situation where the idiotopes of the prepared antibodies are initially *tabula rasa* through the obtained reinforcement signals.

For the ease of the following explanation, we assume that antigen 1 and 2 invade into the immunoid's interior (see Fig.10). In this example, antibody 1 (Ab_1) and 2 (Ab_2) are simultaneously stimulated by each antigen. Consequently, the concentration of each antibody increases. However, since the priority between Ab_1 and 2 is unknown (because idiotopes are initially *tabula rasa*, there are no stimulation/suppression chain), in this case, either of them can be selected randomly.

Now, assuming that the immunoid randomly selects Ab_2

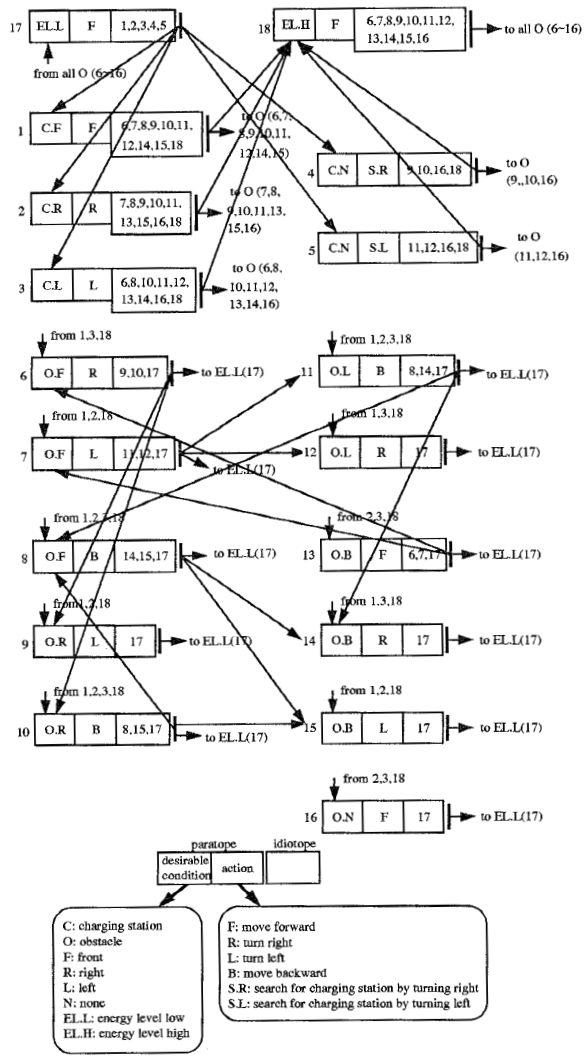


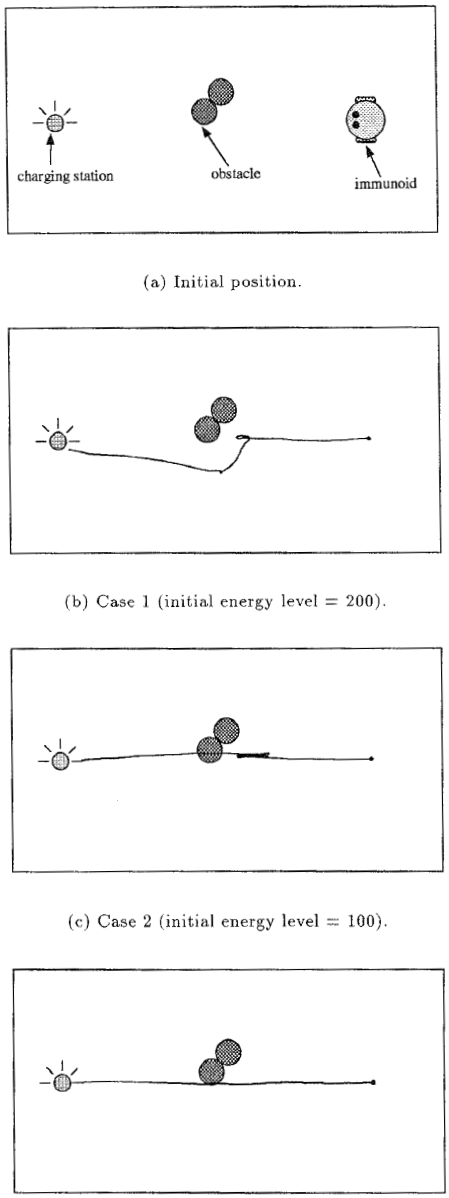
Fig. 8. Prepared immune network.

and then receives a positive reinforcement signals as a reward. To make the immunoid tend to select Ab_2 under the same or similar antigens(situation), we record the ID-number of Ab_2 (i.e. 2) in the idiotope of Ab_1 and increase a degree of disallowance m_{12}. In this study, we simply modify the degree of disallowance as:

$$m_{12} = \frac{T_p^{Ab_1} + T_r^{Ab_2}}{T_{Ab_2}^{Ab_1}} \tag{3}$$

$$m_{21} = \frac{T_r^{Ab_1} + T_p^{Ab_2}}{T_{Ab_2}^{Ab_1}} \quad , \tag{4}$$

where $T_p^{Ab_1}$ and $T_r^{Ab_1}$ represents the number of times of receiving penalty and reward signal when Ab_1 is selected. $T_{Ab_2}^{Ab_1}$ denotes the number of times when both Ab_1 and Ab_2 are reacting to their specific antigens.



(a) Initial position.

(b) Case 1 (initial energy level = 200).

(c) Case 2 (initial energy level = 100).

(d) Case 3 (initial energy level = 50).

Fig. 9. Experimental results.

We should notice that this procedure works to raise the relative priority of Ab_2 over Ab_1. In the case where the immunoid receives a negative reinforcement signal, we record the ID–number of Ab_1 (i.e. 1) in the idiotope of Ab_2 and modify m_{21} in the same way. This works to decrease the relative priority of Ab_2 over Ab_1. In simulations, it is observed that this adjustment mechanism works to improve the performance of the immunoid (e.g. resultant life time) gradually as iterated. We are currently implementing this mechanism into the real experimental system.

B. Innovation mechanism

In the above adjustment mechanism, we should notice that we must still describe the paratope of each antibody in a top-down manner. One obvious and promising candidate to avoid such difficulties is to combine an innovation mechanism with the proposed adjustment mechanism. In the biological immune system, the *metadynamics function* can be instantiated as an innovation mechanism. The metadynamics function works to maintain adequate repertoire of antibodies by incorporating new types (these are generally generated as *quasi-species* through the proliferation process of the activated antibodies) and removing useless ones. Fig.11 schematically shows the concept of the metadynamics function. Incorporating this mechanism is currently under investigation.

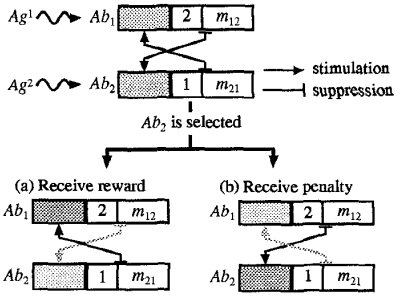


Fig. 10. Proposed adjustment mechanism.

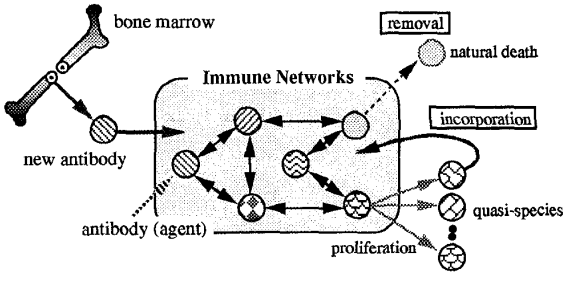


Fig. 11. Metadynamics function.

V. Conclusions and Further work

In this paper, we proposed a new decentralized consensus-making mechanism based on the biological immune system and confirmed the validity of our proposed system by applying to an action arbitration for an autonomous mobile robot as a practical example. And we showed an adaptation mechanism for an adequate arbitration using reinforcement signals.

Since this study is still in a rudimentary stage of investigation, we designed antibodies a priori in a top-down manner. For more usefulness, we must clarify how to combine the proposed adjustment and innovation mechanisms. This is currently undertaking.

Acknowledgments

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