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Moderationism in the Immune System: Gait Acquisition of a Legged Robot Using the Metadynamics Function

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ABSTRACT

Due to the drastic increase of complexity and scale, conventional centralized control methodology has being encountering its limit. To overcome this problem, recently autonomous decentralized control methodology has been attracting a lot of concerns in variety of fields. Biological system is a remarkable instantiation of autonomous decentralized systems and has been expected to provide various fruitful ideas to engineering fields. Among these systems, in this study we particularly focus on the immune system since it has a lot of interesting features such as decentralized regulation mechanism of antibody production, immunological tolerance, metadynamics function and so on. We propose a new adaptation method for decentralized control systems by paying close attention to "moderationism" in the immune system. Finally we will show the possibility of our approach by taking a gait acquisition problem of a hexapod walking robot as a practical example.

1. INTRODUCTION

Adaptation is one of the most essential abilities to cope with the surrounded environment. So far various kinds of adaptation schemes have been proposed in the engineering fields, and they can be mainly classified into two types: learning and evolution. Generally we can not expect the existence of "kind teacher" in the environment, particularly in the field of robotics, supervised learning schemes have very limited of use. Therefore, recently reinforcement learning schemes have been attracting a lot of concerns. However, in this approach the followings are still open questions:

- How do we divide state space appropriately?
- How do we design credit assignment mechanism to accelerate adaptation process?

On the other hand, evolutionary schemes such as genetic algorithms are based on the adaptation in the population level. Therefore, it would be intractable particularly in the field of robotics, since generally adaptation process of robots should be carried out in individual level and also in an on-line manner.

How do living creatures know whether their behaviors have already adapted or not under a certain situation? Okabe et al. recently proposed an interesting idea to answer the above question[1][2][3]. He advocates that for living organisms there exists appropriate input signal levels, and living systems just struggle to develop appropriate signal levels (i.e. not too high and not too low) by changing their internal parameters such as synaptic weights. This can be interpreted as adaptation or learning process from the observer's point of view. They call this hypothesis *moderationism*, and have been applying to the learning of neural networks. Similar ideas are also proposed by Yano et al.[4][5].

On the other hand, besides brain-nerves system living system has another interesting biological information processing called the immune system. This system also plays an important role in coping with dynamically changing environment. Recent studies in immunology clarified that the immune system realizes remarkable functions such as regulation of antibody production, immunological memory and so on by mutual interaction among immune cells. In addition, the immune system dynamically yet appropriately changes its repertoire of

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immune cells (e.g. antibodies) through the recruitment of newly generated cells and removal of useless ones. Therefore, the immune system is expected to provide novel approaches to PDP paradigm. Based on the above facts, we have been trying to engineer methods inspired by the biological immune system and to apply them to robotics[6][7][8][9]. We expect that there would be an interesting AI technique suitable for dynamically changing environments by imitating the immune system in living organisms.

In this paper, we firstly show there also exists a phenomena that can be interpreted as moderationism in the immune system, and then propose a new decentralized control mechanism that elicits appropriate function by combining moderationism in the immune system with the metadynamics function. Finally we will show the possibility of our approach by taking a gait acquisition problem of a hexapod walking robot as a practical example.

2. BIOLOGICAL IMMUNE SYSTEM

2.1 Overview

The basic components of the biological immune system are *macrophages*, *antibodies* and *lymphocytes* that are mainly classified into two types: *B-lymphocytes* and *T-lymphocytes*. B-lymphocytes are the cells maturing in *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 surface. The antibody recognizes specific *antigens* which are the foreign substances such as virus, cancer cells and so on. This reaction is often likened to *a key and keyhole relationship*. To cope with continuously changing environment, living systems possess enormous repertoire of antibodies in advance. On the other hand, T-lymphocytes are the cells maturing in *thymus*, and they generally perform to kill infected cells and regulate the production of antibodies from B-lymphocytes as outside circuits of B-lymphocyte network (idiotypic network) discussed later. Fig.1 schematically illustrates the structure of the immune system.

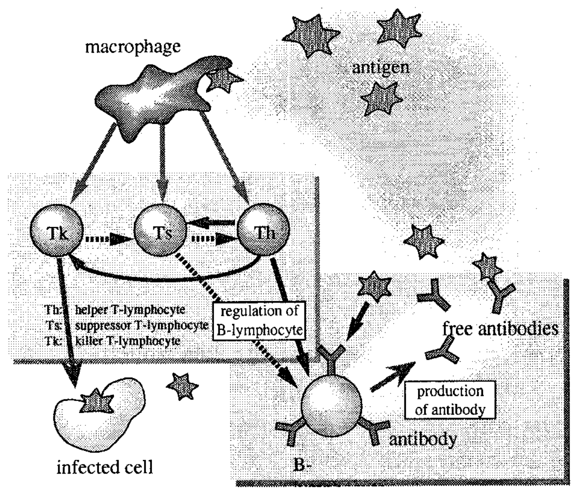

Fig. 1: Schematic view of the immune system.

For the sake of convenience in the following explanation, we introduce several terms from immunology. The key portion on the antigen recognized by the antibody is called an *epitope* (antigen determinant), and the keyhole portion on the corresponding antibody that recognizes the antigen determinant is called a *paratope*. Recent studies in immunology have clarified that each type of antibody also has its specific antigen determinant called an *idiotope* (see Fig.2).

2.2 Jerne's idiotypic network hypothesis

Based on this fact, *Jerne* proposed a remarkable hypothesis called *idiotypic network hypothesis* sometimes called *immune network hypothesis*[10][11][12]. This network hypothesis is the concept that immune cells (i.e. antibodies, lymphocytes) are not just isolated, rather they are communicating to each other. This idea of *Jerne's* is schematically shown in Fig.1. The idiotope Id_1 of antibody 1 (Ab_1) stimulates the B-lymphocyte 2, which attaches the antibody 2 (Ab_2) to its surface, through the paratope P_2. Viewed from the standpoint of Ab_2, the idiotope Id1 of Ab_1 works simultaneously as an antigen. As a result, the B-lymphocytes 1 with Ab_1 are suppressed

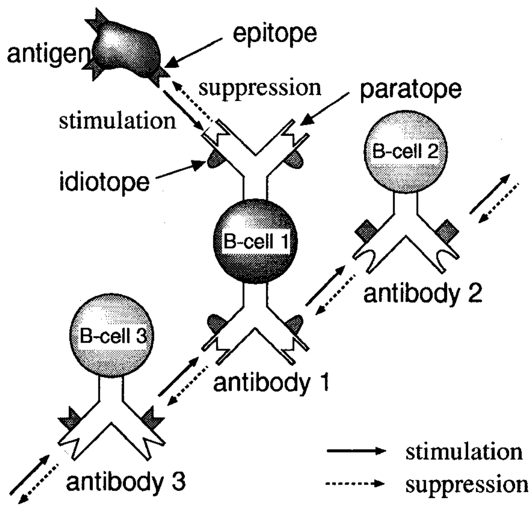

Fig. 2: Immune networks hypothesis.

by Ab_2. On the other hand, antibody 3 (Ab_3) stimulates Ab_1 since the idiotope Id_3 of Ab_3 works as an antigen in view of Ab_1. In this way, the stimulation and suppression chains among antibodies form a large-scaled network and works as a self and not-self recognizer

2.3 Metadynamics function

In the biological immune system, the structure of the network is not fixed, but variable continuously. It flexibly self-organizes according to dynamic changes of environment. This remarkable function, called *metadynamics function*[13][14][15][16], is mainly realized by incorporating newly-generated cells/antibodies and/or removing useless ones. These new cells are generated by both gene recombination in bone marrow and mutation in the proliferation process. Although many new cells are generated every day, most of them have no effect on the existing network and soon die away without any stimulation. Due to such enormous loss, the metadynamics function works to maintain appropriate repertoire of cells so that the system can cope with environmental changes. The metadynamics function would be expected to provide feasible ideas to engineering field as emergent system.

Furthermore, new types of T-cell, which are also generated by gene recombination, undergo the selection in the thymus before they are incorporated into the body. In the selection mechanism, over 95 percent of them would be eliminated (*apoptosis*). The eliminated T-cells would strongly respond to self or not respond to self at all. In other word, the selection mechanism accelerate the system to incorporate new types effectively.

2.4 Moderationism in the immune system

As mentioned above, B-cells produce antibodies to neutralize antigens from their surfaces when they are stimulated. However, this production depends on the degree of the stimulation. As in Fig.3 while B-cells effectively produce antibodies in the case of "moderate" stimulation, antibodies can not be proliferated effectively under the existence of antigen with too high or too low concentration. This phenomena is called *immunological tolerance*. Immunological tolerance implies that moderationism also exists in the immune system.

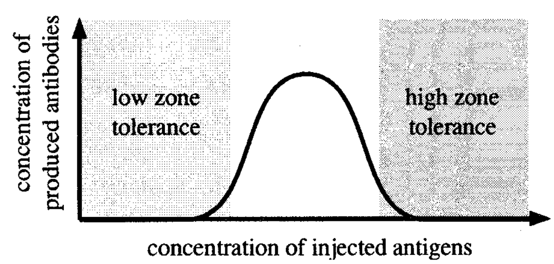

Fig. 3: Immunological tolerance.

3. PROPOSED METHOD

3.1 Self-organization through metadynamics function

Fig.4 shows the basic concept of our proposed method. Each agent (i.e. immune cell) communicates to each other through the stimulation and suppression. This interaction works as a kind of internal feedback loop to regulate the concentration of each antibody. Since this study aims at applying to control robot as a practical example, we assume each agent can generate a certain behavior to interact with its environment. Therefore, we should take into account that an output generated from a certain agent influences other agent through the environment (i.e. external feedback loop). Thus

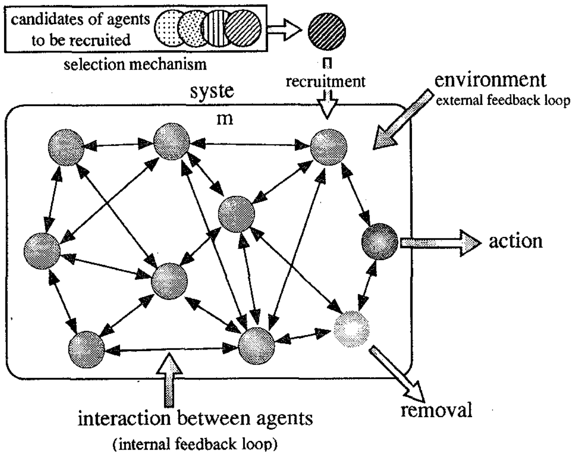

Fig. 4: Basic concept of our proposed method.

stimulation to each agent varies continuously according to the internal and external feedback loop. It should be noted that as described earlier we assume that an agent with too high or too low stimulation dies away due to the high- and low-zone tolerance (needless to say, an agent to be eliminated should correspond to the one that decrease desired performance of the global system. And if an agent is removed, a newly created agent is recruited into the existing immune network through an artificial gene recombination process. In summary, the heart of this study is to develop a decentralized control mechanism that can elicit appropriate function inspired from the immune system, particularly the immunological tolerance and the metadynamics function.

3.2 Application to a gait acquisition problem

As mentioned above, the metadynamics function in our method varies the immune network architecture to settle the input stimulation to each agent into moderate level. Thus important point to be noted is that the state where all agents have moderate stimulation inputs should correspond to the state where the whole system elicits appropriate functions.

In this study, we take a gait acquisition problem of a hexapod walking robot as a practical example. As shown in Fig.5 for successful walking (i.e. not only without falling down but also moves forward successively) each leg must move with an appropriate phase shift among the legs. Thus our aim is that the robot learns autonomously how to walk from scratch by using our immunity-based self-organization mechanism.

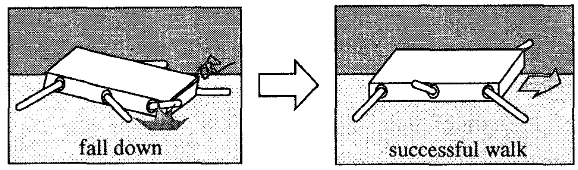

Fig. 5: Gait acquisition problem of a hexapod robot.

The question now arises: in this problem what signals should the system vary to settle onto moderate level through the immunity-based self-organizing process? Obviously, for stable walking each leg must support its body not to fall down by establishing a foothold. In addition, for successive walking, each leg must not only swing backward keeping a foothold but also swing forward in the air for the next step.

In this study, we focus on the fact that for successful walking the load applied to a leg during the stance phase should be within a certain moderate range. This is because a stance leg with too heavy load implies other legs do not support the body properly. Contrary to this, a leg with too light load indicates weight of the body is not distributed to all stance legs properly.

3.3 Dynamics

In this study, for simplicity we do not discriminate B-cells with antibodies. We assign one B-cell to each leg, and this B-cell controls the movement of its leg. Thus the robot has 6 B-cells in total. Additionally, each B-cell has one state variable called concentration and two thresholds (θ_H, θ_L). These values determine how the corresponding leg moves. Fig.6 shows the relationship between these parameters and the movement of the corresponding leg.

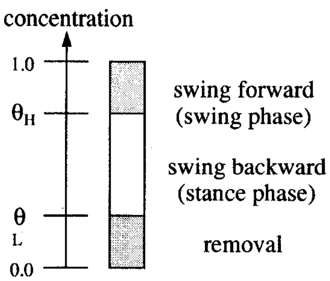

Fig. 6: Relationship between concentration of antibody and its action.

As shown in the figure, concentration is normalized between 0.0 and 1.0. We assume that when the concentration of a certain leg exceeds the prespecified threshold θ_H, the leg swings forward without being off the ground (i.e. swing phase). On the other hand, if the concentration is below θ_H, the leg swings backward with keeping its foothold (i.e. stance phase). θ_L is the threshold used for the metadyanimcs process. If the concentration of a certain B-cell becomes to be below θ_L, the B-cell is removed from the network, and then a newly generated B-cell is recruited instead. This ensures the total number of the B-cells is kept to 6.

Equation (1), (2) and (3) represent the dynamics of the B-cell used in this study.

$$\frac{da_i}{dt} = -k_1\delta_i a_i + k_2\mathrm{Prol}(\sigma_i)a_i - k_3 \quad (1)$$

$$\delta_i = \sum_k m_{ik}a_k \quad (2)$$

$$\sigma_i = \sum_j m_{ji}a_j + k_4 Ag \quad (3)$$

where a_i denotes the concentration of the i-th B-cell, and the first, second and third term of the right hand side in equation (1) represent suppression from other cells, stimulation from other cells and antigen, and dissipation factor, respectively. k_1, k_2 and k_3 are the parameters that determine the relationships among these terms. mji in equation (2) denotes the affinity between i-th and j-th B-cells. Ag in equation (3) is the concentration of the antigen. In this study, we use the magnitude of load applied to each leg as the antigen. k_4 is a coefficient. Prol represents a bell-shaped function to imitate immunological tolerance (see Fig. 7). In this study, we represent this function by combining two sigmoid functions expressed in equation (4).

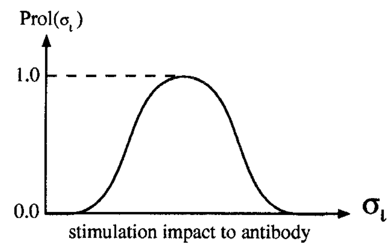

Fig. 7: Function of $\mathrm{Prol}(\sigma)$.

$$\mathrm{Prol}(x) = \frac{1}{1+\exp(24(0.25-x))} \times \frac{1}{1+\exp(24(x-0.75))} \quad (4)$$

B-cells with the above dynamics interacts each other, and this interaction works as a decentralized gait coordination mechanism. It must be noted that a stance leg with too low or too high load can not maintain its concentration of B-cell due to the immunological tolerance, eventually the cell will be removed. In this way, the metadynamics process works to reorganize the gait control network to distribute load to each leg properly.

We are now carrying out several preliminary simulations to verify the feasibility of this approach quantitatively. Some results obtained so far indicate our approach is promising. Detail investigation is currently in progress.

4. CONCLUSION AND FURTHER WORK

In this study, we showed that the immunological tolerance can be interpreted as an instantiation of moderationism. Base on this, we proposed a new decentralized control mechanism that autonomously elicits appropriate function by combining the concept of moderationism with the metadynamics function. One of the advantages expected in our proposed method is that this adaptation process is carried out in an on-line evolutionary manner, and also expected not to suffer from the notorious credit assignment problem.To verify the feasibility, we will carry out simulations and in addition investigate the abilities of our method against fault tolerance (e.g. breakdown of legs), and scalability (i.e. increasing the complexity of the system) in detail.

We are also constructing a real experimental hexapod walking robot to implement this idea to a real system.

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