Gait Coordination of Hexapod Walking Robots Using Mutual-Coupled Immune Networks

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ABSTRACT

Biological information processing systems can be said as one of the ultimate decentralized systems, and have been expected to provide various fruitful ideas to engineering fields, especially robotics. Among these systems, brain-nervous system and genetic system have already been widely used by modeling as neural networks and genetic algorithms, respectively. On the other hand, immune system also plays an important role to cope with dynamically changing environment by constructing self-nonself recognition networks among different species of antibodies. And this system has a lot of interesting features such as learning, self-organizing abilities and so on viewed from the engineering standpoint. However, immune system has not yet been applied to engineering fields so far notwithstanding its important role. In this paper, we propose a new hypothesis concerning the structure of immune system, called mutual-coupled immune networks hypothesis, based on recent studies on immunology. And we apply this idea to gait acquisition of a hexapod walking robot as a practical example. Finally, the feasibility of our proposed method is confirmed by simulations.

1. Introduction

Biological systems in living organisms can be regarded as ultimate distributed information processing systems, and are expected to provide various feasible ideas to engineering fields such as robotics and so on. These systems can be mainly classified into the following four systems: 1) *brain-nervous system*, 2) *genetic system*, 3) *endocrine system*, and 4) *immune system*. Among these systems, brain-nervous and genetic systems have already been applied to engineering fields by modeling as neural networks and genetic algorithms, respectively, and they have been widely used in various fields. The other systems (*i.e.* endocrine and immune systems), however, have not been applied to engineering fields notwithstanding their important roles.

Among these two systems immune system works to protect living organisms and cope with dynamically changing environment against countless unknown materials such as virus and so on. This ability is just what we need for autonomous mobile robots. Therefore, we expect that immune system would provide a novel information processing methodology to engineering fields, especially robotics. Recent studies on immunology have clarified that this outstanding abilities are realized by constructing self-nonself recognition network among different species of antibodies, called *immune networks*[1]-[5]. Moreover, immune system has various interesting features such as self-organization, learning ability and so on. Based on the above fact, we have been trying to construct the engineering models of immune system, and apply to robotics and so forth[6]-[8].

In this paper, we propose a new hypothesis on the immune system called *mutual-coupled immune networks* hypothesis based on the knowledge from the recent immunology, and apply this idea to a gait coordination of hexapod walking robots as a practical example. So far various methods have been proposed to realize a successful walking patterns of multi-legged walking robot from the decentralized control standpoints such as neural networks and so on[9]-[15]. Against these methods, we take a quite different way by paying close attention to reactions among antigens and antibodies. To confirm the validity of our proposed method, some simulations are carried out.

2. Immune networks

2.1 Structure of immune system

The main task of immune system is to detect and/or eliminate the *non-self* materials called *antigens* such as virus and cancer cells and so on that come from inside and outside of the living system. The basic components of the immune system are *lymphocytes* and these are mainly classified into two types, called *B-lymphocytes* and *T-lymphocytes*(Fig.1).

B-lymphocytes are the cells produced from *bone marrow*. In a human body roughly 10^{12} distinct types of B-lymphocytes are contained and each of which has distinct chemical structure. Note that the number of neurons in a human brain is at most 10^{10}. Each type of lymphocyte produces "Y" shaped *antibodies* from its surfaces if the antibody detects its specific antigen like a key and lock relationship.

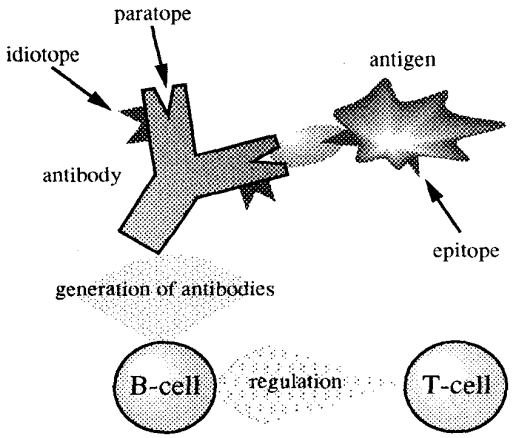


Fig.1: Structure of immune system.

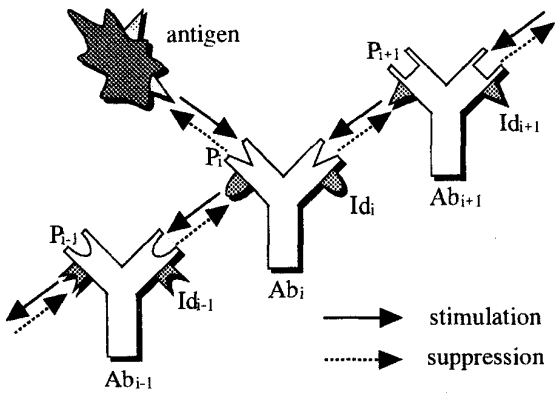


Fig.2: *Jerne's* idiotypic network hypothesis.

On the other hand, T-lymphocytes are the cells produced from *thymus*, and are classified into three different types; *suppresser T-lymphocytes, helper T-lymphocytes* and *killer T-lymphocytes*. Among these T-lymphocytes, suppresser and helper T-lymphocytes perform to regulate the production of antibodies from B-lymphocytes as outside circuits of B-lymphocyte network (idiotypic networks) described in the next subsection.

2.2 Jerne's idiotypic network (immune network) hypothesis

Recent studies on immunology have clarified that antibodies are not just isolated, namely they are communicating to each other among different kinds of antibodies.

For the sake of convenience in the following explanation, we firstly 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*. Each type of antibody has also its specific antigen determinant called *idiotope*(see Fig.1).

Based on this fact, *N.K.Jerne*, who won the Nobel prize for immunology, proposed a remarkable hypothesis: *idiotypic network hypothesis*[4]-[5]. This network hypothesis, which is fundamentally based on

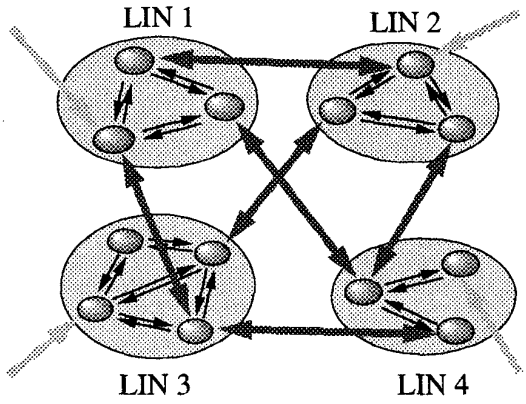


Fig.3: Mutual-coupled immune networks hypothesis.

clonal selection theory[16], is the concept that the immune system is constructed as a large-scale closed system of lymphocytes through mutual interaction between different species of lymphocytes. This idea of Jerne's is schematically shown in Fig.2. The idiotope Id*i* of antibody *i* (Ab*i*) stimulates the B-lymphocyte *i*-1, which attaches the antibody *i*-1 (Ab*i*-1) to its surface, through the paratope P*i*-1. Viewed from the standpoint of Ab*i*-1, the idiotope Id*i* of Ab*i* works simultaneously as an antigen. As a result, the B-lymphocytes *i* with Ab*i* are suppressed by Ab*i*-1. On the other hand, antibody *i*+1 (Ab*i*+1) stimulates Ab*i* since the idiotope Id*i*+1 of Ab*i*+1 works as an antigen for Ab*i*. In this way, these stimulation and suppression chains among antibodies form the large closed chain loop which works as a self and non-self recognizer. The heart of *Jerne's* idea is that the self-nonself recognition in the immune system is carried out at system level.

2.3 Proposed mutual-coupled immune network hypothesis

The central idea of the above-mentioned *Jerne's* hypothesis is very attractive viewed from the engineering standpoint. However, such large-scaled connections among antibodies have not yet been ascertained experimentally. Merely at most four or five chains among antibodies have been discovered so far[17]. From the fact that the immune system successfully works to maintain the living organisms in spite of such small-sized connections, it seems reasonable to propose the following hypothesis. That is, immune system accomplishes its remarkable ability by mutually communicating among small-scaled networks each of which has a specific task. In other words, immune system is constructed by forming large-scaled immune networks through the interaction among small-scaled networks. We call this idea *mutual-coupled immune networks* hypothesis. And for the sake of convenience, we call this small-scaled immune network *Local Immune Network* (LIN). Our proposed hypothesis is schematically illustrated in Fig.3. In this study, we apply the above-mentioned idea to gait control of a hexapod walking robot as a practical example.

3. Gait control for a multi-legged walking robot

Recently, multi-legged walking robots have been expected to expand working fields of robots since they can walk on rough terrain such as another planet and so on. Therefore, many attentions have been paid to develop their control methods. In unstructured environments, we must consider the situation that legs of the walking robot are sometimes disturbed. As a result, the robot often can not walk forward and/or fall down. To avoid such situations, techniques that automatically maintain adequate leg coordination are highly required. Note that this problem also provides one of good examples of self-organizing problems, since each leg must coordinate its movement adequately to maintain reliable locomotion using information about the states of other legs.

So far various control methods for gait control of multi-legged walking robots have been proposed. Most conventional approaches to this problem were based on the pre-programmed leg sequence manners. As a result, they suffered from the brittleness against internal/external changes. Against these methods, *Brooks'* lines of works from the standpoints of decentralized control methodology have been proved to be very successful [10][12]. He used the network of the augmented finite state machines each of which corresponds to a specific competence module. However, this methodology has some drawbacks such as great efforts may be required to construct competence modules properly. Moreover, as *Bekey* and his collaborators mentioned in their work[14], small changes in networks of finite state machines often causes fatal changes in resultant behaviors, whereas this is not usually so serious in neural networks and so on. Therefore, alternative approaches based on the neural network architecture have been also proposed so far[9][11][14][15].

In contrast to the aforementioned stream of works, we utilize the dynamics of immune networks to obtain reliable gait patterns. As a rudimentary stage of investigation, we take a hexapod walking robot as a practical example, and assume that this robot walks maintaining static stability (*i.e. duty ratio* > 0.5).

4. Immunological approach to gait coordination problem

4.1 Description of leg movement

To implement our proposed hypothesis into gait coordination problem of a hexapod walking robot, we firstly assign one Local Immune Network(LIN) to each leg of the simulated walking robot (*i.e.* there are six LINs in total). This means that each LIN controls its corresponding leg movement. Based on the Behavior-based AI manners, we divide a leg movement into the following four competence modules:1) *swing-backward-behavior*, 2) *retract-behavior*, 3) *swing-forward-behavior*, and 4) *protract-behavior*. These defined four competence modules are schematically depicted in Fig.4.

Next, we consider the structure of antibodies

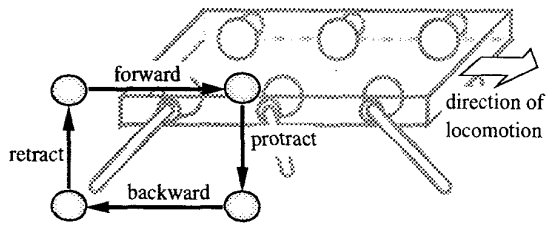


Fig.4: Defined leg movement modules.

		paratope	idiotope
backward_behavior	Ab^{SS}	support	support
retract_behavior	Ab^{ST}	support	transfer
forward_behavior	Ab^{TT}	transfer	transfer
protract_behavior	Ab^{TS}	transfer	support

Fig.5: Defined four antibodies.

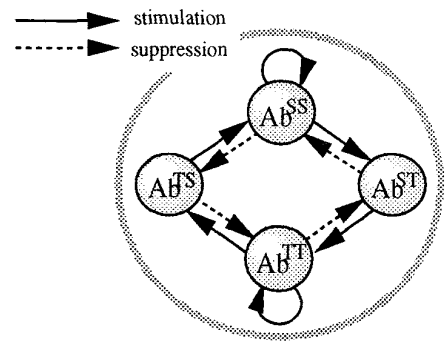


Fig.6: Local Immune Network of a leg movement.

suitable for this leg coordination problem. As mentioned earlier, the identity of a specific antibody is generally determined by the structure (shapes) of its paratope and idiotope. In this study, we assign current and expected next states of a leg to paratope and idiotope, respectively. We should notice that a leg state can be simply classified into *support* and *transfer* states. Support state means that a leg is on the ground,whereas transfer state is off the ground. From the above consideration, we represent the above four competence modules as antibodies. On this immunological basis, the antibody corresponds to retract behavior, for example, can be described by 'support' in paratope and 'transfer' in idiotope, since retract behavior changes the state of the leg concerned from 'support' to 'transfer'. The other antibodies can be derived in the same way. The results are shown in Fig.5.

For the sake of convenience, we represent the antibodies correspond to swing-backward, retract, swing-forward and protract behaviors as Ab^{SS}, Ab^{ST}, Ab^{TT}, and Ab^{TS}, respectively. From these four antibodies, we can easily construct a LIN through connections among the predefined paratopes and idiotopes as shown in Fig.6.

4.2 Generation of leg movement

In this study, selection of antibodies is simply assumed in a *winner-take-all* fashion. Namely, at an

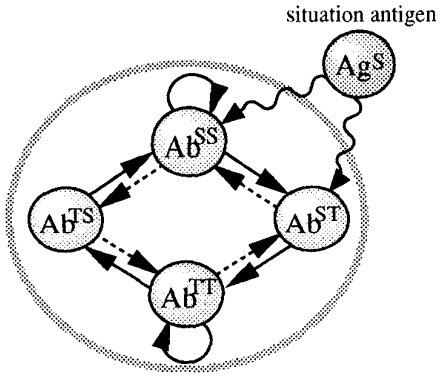


Fig.7: Situation antigen in the case of stance phase.

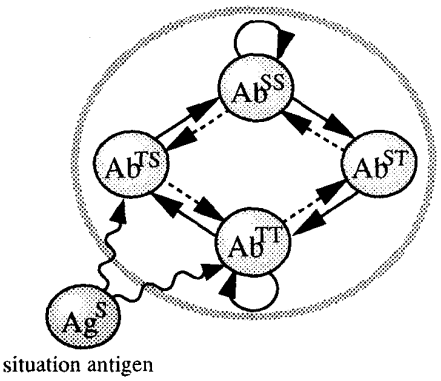


Fig.8: Situation antigen in the case of swing phase.

arbitrary point of time, only one antibody is allowed to activate and act its corresponding behavior to the world if its concentration is highest among four antibodies. As described before, antibodies vary their concentrations according to the mutual interaction through their paratopes and idiotopes. To realize successful walking, it is desirable that the predefined antibodies are selected periodically (*i.e.* in the order of Ab^{SS}, Ab^{ST}, Ab^{TT}, and Ab^{TS} for forward locomotion). Although the obtained structure of LIN as shown in Fig.6 potentially has an ability to generate a cyclic movement, we introduce the following two devices. Firstly, we introduce the concept of antigens, called *situation antigens* Ag^S, to ensure the effective periodical leg movement. In this study, current state of the leg concerned is given as the situation antigen, and fed into the LIN. Namely, if a leg is on the ground, situation antigens Ag^S are put into the corresponding LIN and stimulates the antibodies of Ab^{SS} and Ab^{ST}, since these antibodies have paratopes where the state 'support' is written in(see Fig.7). On the other hand, if a leg is off the ground, the situation antigens Ag^S are put into the LIN to stimulate the antibodies of Ab^{TT} and Ab^{TS} (see Fig.8). Another device is concerned with the concentrations of the situation antigens. Obviously, each leg movement is physically limited within the pre specified stance width. For example, let us assume that a leg is in the 'transfer' phase (swing phase). This leg will reach its anterior extreme position before long, and then the leg should not take swing-forward behavior anymore but

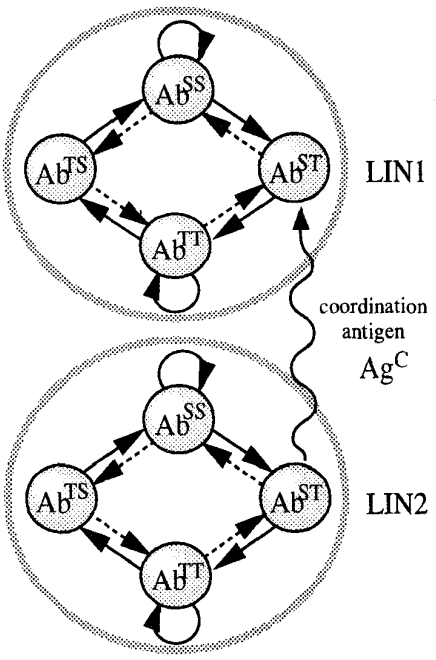


Fig.9: Mutual coupling among LINs through the coordination antigen.

protract behavior. To reflect the physical limits (*i.e.* anterior and posterior extreme positions) properly, we change the concentration of situation antigen according to the current position of the leg concerned. For instance, when the leg is on the ground and at the anterior extreme position, the situation antigen merely stimulates Ab^{SS}.

4.3 Mutual coupling among Local Immune Networks

Although the LIN can realize the periodical leg movement based on the above-mentioned dynamics of the immune system, we should notice that each LIN still acts isolatedly. For the realization of successful gait patterns, we must consider how we coordinate the relationships among LINs adequately. We approach to this problem using mutual-coupled immune networks hypothesis proposed in the previous section (see Fig.3). Again, the heart of the concept of our proposed hypothesis is that the remarkable ability of the immune system is obtained by mutual interactions among LINs.

To implement our proposed hypothesis into this problem, we introduce the concept of *coordination antigen* Ag^C in addition to the pre mentioned Ag^S. This concept is schematically depicted in Fig.9. In the figure, the antibody Ab^{ST} in LIN2 acts as the coordination antigen to the antibody Ab^{ST} in LIN1. Note that the arrow from Ag^C (in this case, Ab^{ST} in LIN2) represents the direction of stimulation, and there also exists the suppression in opposite direction.

Using this concept, we expect the phase of each LIN shifts from the isolated situation to cooperative situation suitable for successful gait patterns. The concentration of each antibody in a LIN is determined as:

$$\frac{dB_{ik}}{dt} = (k_a \cdot S_{ik} - k_d) \cdot f(B_{ik}) + k_{supply} \quad (1)$$

$$S_{ik} = \sum_j a_{jk,ik} \cdot B_{jk} - \sum_l a_{lk,ik} \cdot B_{lk} + Ag^S_{ik} + Ag^C_{ik} \quad (2)$$

$$Ag^C_{ik} = \sum_{k' \neq k} a_{ik,jk'} \cdot B_{jk'} \quad (3)$$

where B_{ik} denotes the concentration of i-th antibody in k-th LIN. Ag^S_{ik} and Ag^C_{ik} represent the concentrations of situation and coordination antigens which affect the i-th antibody in k-th LIN, respectively. k_a is the coefficient for the strength of stimulation and suppression effects. k_d and k_{supply} determine the natural death and supply from bone marrow, respectively. S_{ik} denotes the total sum of stimulation and suppression effects given to the antibody concerned. And $a_{jk,ik}$ represents the affinity (matching ratio) between i-th and j-th antibodies in k-th LIN. Finally, $f()$ means a squashing function such as sigmoid function.

From the above arrangements, this problem consequently results in finding appropriate interactions among LINs in terms of coordination antigens. Although the real immune systems have attractive learning abilities, much still remains for further investigation viewed from the standpoints of not only engineering but also immunology. Thus, in this paper, we use Genetic Algorithms (GA) to find out appropriate coordination antigens, namely connections among LINs.

4.4 Decision of relationships among LINs using GA

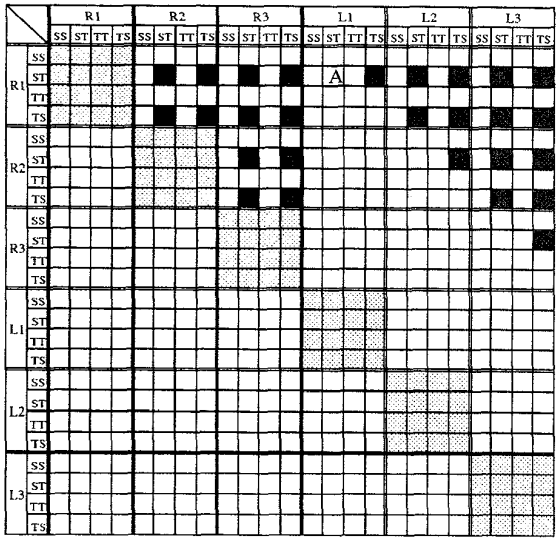
Possible candidates foe coordination antigens among LINs are listed in Table 1. In the table, R1, R2, R3 represents the front, middle and back leg on the right side of the body, respectively. Legs on left side also represented in the same way. Note that the connection signed 'A' denotes that the antibody Ab^{ST} in LIN R1 stimulates the antibody Ab^{ST} in LIN L1 as the coordination antigen, and is suppressed at the same time.

For simplicity, in this study, we use the following assumption for GA-search as:

- •The connections among LINs are limited between the antibodies Ab^{ST} and Ab^{TS}. The reason for this assumption is that these antibodies determine the timing of phase change between stance and transfer.
- •The connections are symmetric about the longitudinal body axis.
- •All the affinities (connection weights) between coordination antigens and their corresponding antibodies are the same.
- •Antibody does not act as coordination antigen to the antibodies in the same LIN.

From these assumptions, the number of possible candidates for coordination antigens can be eventually reduced to 27 depicted in the heavily shaded portions in the table. Then we represent these relations by one-dimensional chromosome, and we assign one of the following values into each locus: 1(stimulation), −1 (suppression) and 0(no connection). For the evaluation

Table 1: Possible connections among LINs.



of chromosomes, we use the following falling ratio as fitness:

$$fitness = \frac{duration\ of\ falling\ down}{pre\text{-}specified\ test\ duration} \quad (4)$$

In this method, it is ensured that the leg moves periodically for forward locomotion, the falling ratio is in inverse proportion to the forward distance that the robot walks.

5. Simulation results

To confirm the validity of our proposed method, we carried out some simulations using Simple GA under the conditions of duty factor 0.6, population size 20, crossover rate 0.4 and mutation rate 0.2. Fig.10 shows the transition of average and best falling ratios. From the figure, it is understood that the falling ratio is settled to 0.0 at the 18th generation. This means that we obtain appropriate relationship among LINs suitable for successful walking. Fig.11 indicates the relationships among LINs by decoding the obtained best chromosomes at 18th generation. In the figure, direction of arrow means the one of stimulation. Note that there also exists suppression effects in the opposite direction.

Next, to evaluate the robustness of the obtained above mutual-coupled immune networks, we forcibly fixed the movement of the leg R1 for some duration. The result is shown in Fig.12. It is comprehended that after the input of disturbance the simulated robot soon converges to the suitable gait. In this case, we inputted the disturbance to the leg R1, we have confirmed that the robot converges the suitable gait even if we input the disturbance to any leg.

6. Conclusions and further work

In this study, we proposed a new interpretation of immune system, called mutual-coupled immune network hypothesis from the recent knowledge in

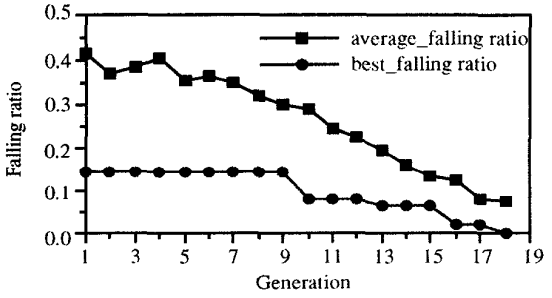


Fig. 10: Transition of falling ratio.

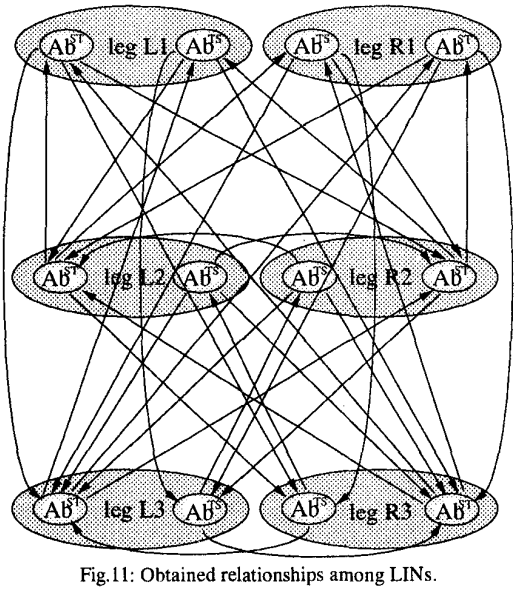


Fig.11: Obtained relationships among LINs.

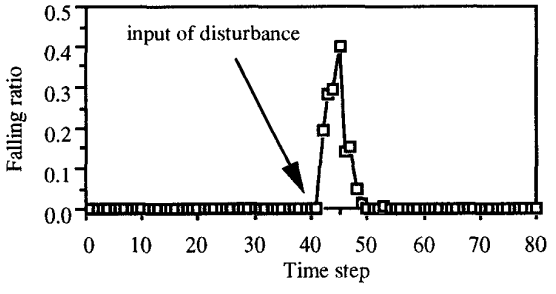


Fig.12: Tolerance against disturbance.

immunology. And we applied this idea to gait control of hexapod walking robots as a practical example. From the simulation results, it is clarified that our proposed method is robust against inputs of disturbance.

To make our method more feasible, it would be interesting to incorporate on-line learning mechanisms based on the immunological point of view to obtain relationships among LINs. Moreover, it is highly necessary to devise the structure of LINs to cope with unstructured environments and fault tolerance such as breakdown of a leg and so on. These are currently under investigation. Although our method is still in the rudimentary stage, we expect that immune system would provide novel PDP models suitable for engineering fields. Currently, we are constructing a real hexapod walking robot to confirm the feasibility of our method experimentally.

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