An Immunological Algorithm and Its Application to Disturbance Rejection *

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Key Words - Adaptive control, disturbance rejection, immune systems, diversity, genetic recombination, simulation.

Abstract

A new information processing architecture is extracted from immune systems. By focusing on informational features of immune system (i.e. specificity, diversity, tolerance, and memory), an immune algorithm is proposed. The algorithm proceeds in three steps: diversity generation, establishment of self-tolerance, and memorizing non-self. Agent-based architecture based on the local memory hypothesis and network-based architecture based on the network hypothesis are discussed. Agent-based architecture is elaborated with the application to control system where the knowledge about disturbances is not available. Adaptive disturbance neutralizer is formalized and simulated for a simple plant.

1 Introduction

Biological systems have sophisticated information processing capabilities. Information sciences have been paying attention on these information processing mechanism, especially that of the brain and the sense organs. *Neural Networks*, which hinted from neural systems in brain, has been used in many patten recognition. Several parallel and distributed models based on the neural net have been proposed and their learning algorithms studied, with the hope of giving a breakthrough for pattern recognition problems such as voice recognition and image recognition. In recent years, computational method based on the analogy of biological information processing has been paid much attention. *Genetic Algorithm*, which mimic the adaptation of biological systems in genetic level, has been collecting wide attention as a new search method in many fields.

Yet another important information processing can be found in immune systems, although we cannot be conscious of the activity. The motivation of our research is to (1) explore the

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principle of information processing done in immune system, and (2) develop information models based on the principle in immune systems, as the neural net is developed based on that in brain systems. Our aim, therefore, is to build new information models, rather than to build a precise model of immune systems. Although complete imitation of biological information processing may not lead to the good information processing by machine, some of their sophisticated way of information processing gives us a new paradigm. Immune system, although it has been studied extensively for a long time in immunology, relatively not much has been studied as as information processing models.

In this paper, we will extract the recognition mechanism as well as learning mechanism of a immune system as a pattern recognizer. Section 2 summarizes findings in immunology and discusses informational features of immune system.Section 3 proposes an immune algorithm which is extracted from immune system discussed in section 2. Section 4 elaborates the immune algorithm to apply it to a certain control system. Adaptive disturbance neutralizer is formalized and simulated for a simple plant, too.

2 Immune Systems and Information Processing

Mathematical models of immune systems have been studied in mathematical immunology [1, 2, 3] focusing on population dynamics of specific cells and antibody, inspired by the concept of idiotypic network [4]. However, most of them tried to explain quantitative aspect of immunological phenomena. Only few [5, 6, 7, 8] tries to extract information processing principles from the immune systems for the application to information processing systems. In this paper, rather than building a detailed mathematical model of immune systems, we tried to explore the principle in immune system focusing on the information processing capabilities, such as pattern recognition and learning, as done in artificial neural networks and genetic algorithm.

Important findings in immunology from a viewpoint of information processing may be summarized under the following keywords:

- Specificity: Each recognizer (B-cell and T-cell) reacts only against a specific non-self pattern. (*Clonal selection hypothesis* as opposed to *Instruction hypothesis.*)
- Diversity: Huge diversity in terms of the specificity above is generated in one generation by genetic recombination as opposed to being inherited from parents to child. (*Somatic hypermutation hypothesis* as opposed to *Germ line hypothesis.*)
- Tolerance: Self-tolerance may be acquired and induced in an early developmental stage of immune system and when it encounters large amount of antigen of the same type.

- Memory: Immune system has a (short-term) memory in the sense that it can respond more efficiently to the antigen in second response. This memory may be attributed to network level activity (*network hypothesis*) or unit (cell) level activity (*local hypothesis*).

We will discuss implications of each of the features above. Recognition of self/non-self mechanism seems to be controversial, however the recognition process is trigerred by antigen recognized by B-cell or T-cell receptor. At this level of trigerring, these cells react against only a specific antigen using spatial complementarity (as explained by the metaphor of key-keyhole relation). One of biological information principle extracted is that unit (cell) has homogeneous in structure and its potential, but it will be specialized in its function.

As for *diversity*, it is novel to artificial systems to prepare possible combinations beforehand, since economic and resource restriction is critical for artificial systems. However, this feature certainly seems to be imperative under the situation where the system is exposed to totally unpredictable environment. This feature is made possible by the other principle of biological system; homogeneous unit can self-replicate with mutation and crossing-over. Generation of diversity by combinatorial mechanism may potentially give insight to building new information models, since most of the current models depend upon copying for storage and transfer of information.

Tolerance and *Memory* can be regarded as the adaptation process to self and non-self, respectively. Adaptation to self seems to be first carried out to be insensitive to the self. In this sense, acquiring self-tolerance can be seen as a learning process for *long-term memory* and memorizing non-self can be seen as a learning process for *short-term memory*. For the short-term memory, whether the memory is attributed to the state change of sensitized cell, or attributed to the structural and parametric change of the entire network remains to be controversial [11]. Although recent immunology seems to favor the former, both of them can be used as an information processing system. We call the former *agent-based* architecture and the latter *network-based* architecture. For the *agent-based* architecture, more importance is placed on the principle of biological system that the unit can change its attributes such as mutation rate, life span, reproduction rate etc., trigerred by some events. For the *network-based* architecture, the importance is placed on the other principle of biological systems: units can communicate and cooperate during both developmental and working phases.

There already have been proposed several *network-based* architectures [6, 9, 10]. This paper will demonstrate the *agent-based* architecture in the application to the adaptive disturbance neutralizer presented in section 4. The immune algorithm proposed in this paper, is neutral to the architecture as presented in the next section. So far we have discussed informational feature of immune systems, which we will be elaborated as an immune algorithm in the next section. We also extracted some principles of biological systems, which may be common to several levels (i.e. such as cell, individual, and social

group) for self-organizing system. Although more elaboration and refinement is required for the extracted principles, they would give some implications for artificial systems. However, this issue is out of scope of this paper. At this point, we note that although we focus on the specific feature of immune system, its information processing seems to share common background with many other parallel distributed systems[1] . In fact, compared with neural networks, immune system is dedicated to maintain material identity of the self, while neural system is dedicated to mental identity of the self. In this level, genetic system may be dedicated to maintain the identity of species.

3 The Immune Algorithm: A New Paradigm of Learning for Pattern Recognition

The most naive immune algorithm has the following three steps.

1. *Generation of Diversity*: Diversity of recognizer[2] in its specificity is generated.
2. *Establishment of Self-Tolerance*: Recognizers are adjusted to be insensitive to *known pattern*(self) during developmental phase.
3. *Memory of Non-Self*: Recognizers are adjusted to be more sensitive to *unknown pattern* (non-self) during working phase.

In the step of *Generation of Diversity*, genetic coding for recognizer could be used in a similar manner to that of *Genetic Algorithm*. In that case, the genetic code of recognizers will be recombined to guarantee the diversity of their specificity. Then, recognizers are developed from their coding in this step. In the step of *Establishment of Self-Tolerance*, the recognizers which are specific to *self* pattern are removed for *agent-based* architecture. For the *network-based* architecture, structure and parameters of the network will be adjusted so that the system become insensitive to the self. In the step of *Memory of Non-Self* for *agent-based* architecture, the recognizers which actually recognized *the unknown pattern* during working phase will be activated. Activated recognizers would have any of the following properties resulting in higher affinity with the encountered non-self (for local and cell-based memory as opposed to network memory).

[1]General character of biological information processing is that it has physical and material basis by interaction and synthesis of high molecules as opposed to pure information basis found in the computer. Immune system is not exception. Recognition is done by *physically moving* units (i.e. lymphocyte). Communication among units are done physically by interleukin. Its recognition is determined by physical pattern of recognizing and recognized site (i.e. paratope and epitope). Its action is physical (i.e. removal of non-self and keeping physical identity of the self.)

[2]We will use the word "recognizer" for the unit (cell) that has only recognizing and communicating capabilities. The word "agent" is used for the unit that has more intelligence and autonomy; adaptation and self-replication capability as well as recognition capability.

- Elongation of life span or lower death rate to attain immune memory,
- Reproduction of clones (i.e. recognizers of same type),
- Higher rate of mutation.

For *network-based* architecture, parameters of the network are adjusted to be more sensitive to the encountered pattern. Figure 1 shows an schematic diagram of the immune algorithm for an agent-based architecture.

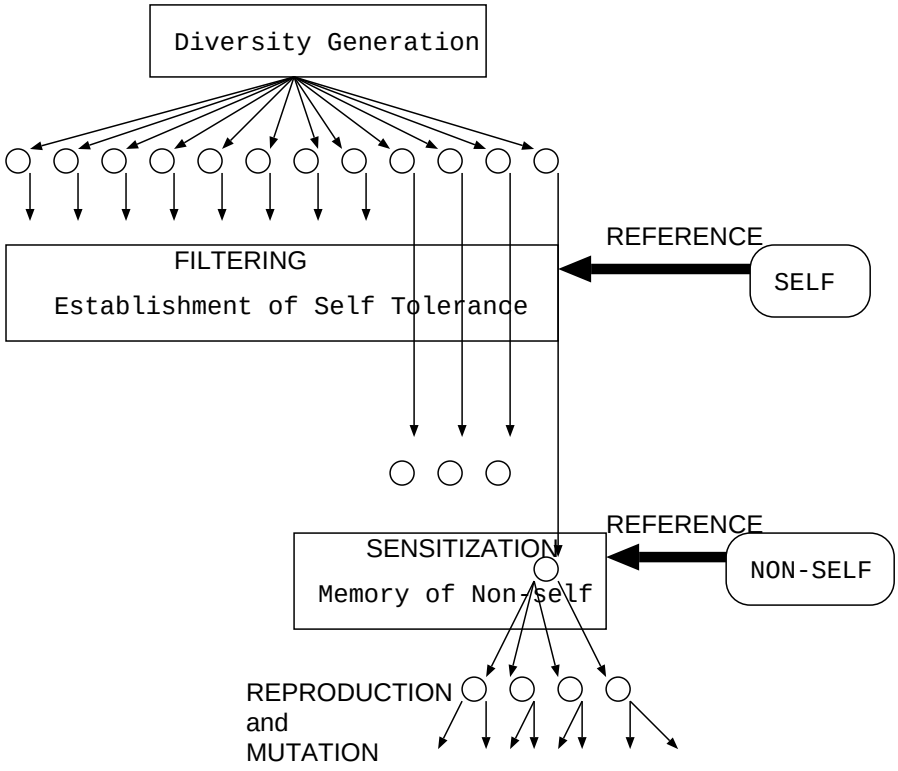

Figure 1: Immune Algorithm for An Agent-based Architecture

For the network-based architecture, the network will be structurally adjusted at the step of *Establishment of Self-Tolerance* rather than filtering self-sensitive agents. The adjustment of the network at the step of *Establishment of Self-Tolerance* is more drastic with structural change than that at the step of *Memory of Non-self*. In the step of *Memory of Non-self*, network parameters are adjusted to be more sensitive to the non-self presented

rather than reproducing and mutating for higher affinity. Generally, in these steps *network-based* architecture is not as straightforward as *agent-based* architecture where only filtering and sensitization of recognizers are carried out.

As explored above, immune algorithm is fundamentally similar to evolution mechanism except it is controlled and accelerated. It is the adaptation process referring not only to environment as in the step of *Memory of Non-Self* but to the self as in the step of *Establishment of Self-Tolerance*. It is an evolution in one individual in one life span rather than in a species in many generations.

The immune algorithm can apply to any system where environment is unpredictable. One typical domain may be fault diagnostic systems where the knowledge of fault is intrinsically unpredictable. In other words, fault is by its nature unexpectable, since expectable event can be generally avoidable by design. The technique seems promising, since the diversity of faults is enormous as the system becomes large-scale. Another domain may be control of systems where the knowledge about disturbances imposed is not available. This technique may be especially required for the situation that control signal and disturbance cannot be discriminated in the signal level. We will discuss the application to the control domain in the next section. In conventional control system, disturbance recognizer and controller are physically and conceptually separated. However, in this adaptive disturbance neutralizer, they are identified as recognizers. Recognizers are rather divided by the disturbance patterns upon which recognizers act. To each disturbance pattern of signals, different recognizer which is capable of producing neutralizing signal is supposed to be activated. That is, each recognizer has the capability of recognizing one specific disturbance signal and that of neutralizing the disturbance.

The next section formalizes the adaptive disturbance neutralizer based on the *agent-based* architecture discussed in the this section.

4 Applications of the Immune Algorithm to Adaptive Disturbance Rejection

The disturbance decoupling or the disturbance rejection is the one of the central issues in control problems. A control system is said to be disturbance decoupled if the output of the system is completely insensitive to disturbances to the system. Extensive research have been carried out on this problem. For instance, if the plant to be controlled is linear and time invariant necessary and sufficient conditions for the existence of disturbance decoupling controller is well-known [12].

If these conditions are satisfied and if exact models of the plant and the disturbance generator are known, a controller which rejects disturbances can be constructed easily.

If the knowledge concerning the plant and/or the disturbances is not complete, adaptive

versions of disturbance decoupling controller would be available [13]. The principle of the conventional adaptive control is to estimate the model of disturbances along with the model of the plant and to use the models to construct adaptive controllers.

In this section another approach to adaptive disturbance rejection is formalized based on the agent-based architecture discussed in the previous sections. Instead of estimating the models of the plant and the disturbances, a number of agents, called recognizers, are prepared a priori. Each recognizer is activated to a disturbance peculiar to the recognizer, and the activated recognizer injects a signal, called neutralizing signal, to the control system. The total sum of the neutralizing signal is to cancel the effect of disturbances to the control system.

4.1 Control architecture

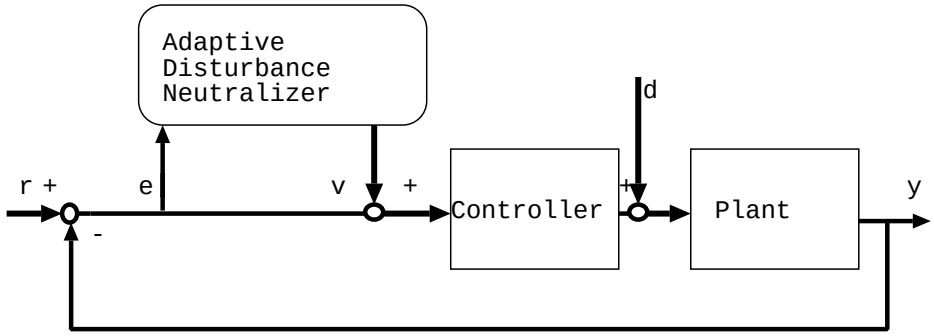

Figure 2: Block Diagram of Adaptive Disturbance Neutralizer

Fig. 2 shows a schematic diagram of the adaptive control system with disturbances neutralizer. In the figure, the block of the adaptive disturbance neutralizer is composed of a system of recognizers connected in parallel.

Each recognizer is essentially a shaping filter, which receive the error signal e as its input and the input is shaped to make the output of the filter. The structure and the elements of the neutralizer is variable during the operation of the control system. Unnecessary elements become inactive or are deleted, and new elements are created.

For simplicity, only periodical disturbances are considered. This assumption implies that the disturance can be represented by a sum of a finite number of determnistic and periodic functions. In this case, every element of the neutralizer has a pair of signals of the finite lengths. One of its pair, $x_j(n)$ represents a pattern of input signal to the plant. Another

element $y_j(n)$ of the pair represents the output of the plant for the input $x_j(n)$. The pairs of signals

$$\{x_j(n), y_j(n), \quad n = 1, 2, \cdots, N_j\}$$

are generated by some means a priori. The problem concerning the generation of the pairs of the signals will be discussed later. The idea of the neutralizer and the pairs of the signals in each component (recognizer) is illustrated in Fig. 3.

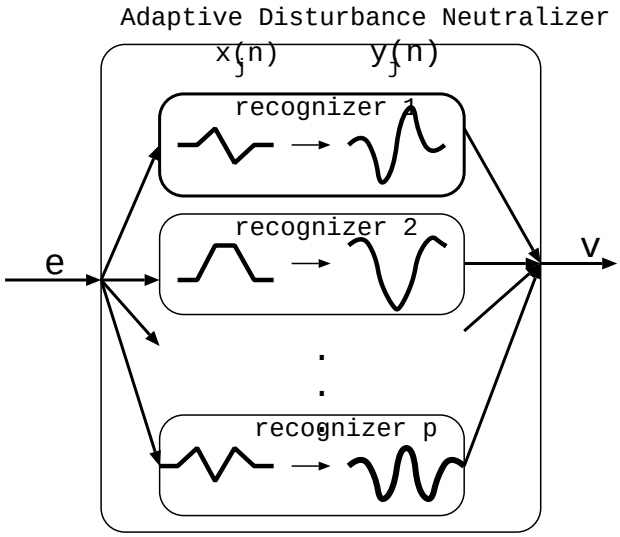

Figure 3: Adaptive Disturbance Neutralizer Consisting of Recognizers Working in Parallel

During the operation of the control system, jth recognizer tries to finds a pattern embedded in the signal $e(\cdot)$, which is similar to the signal $y_j(\cdot)$. If it find a similar pattern, the recognizer evaluate the periodicity of the pattern. If the pattern appears periodically in the signal $e(\cdot)$, jth component injects the signal $x_j(\cdot)$, amplified suitably, to reduce the effect by the disturbance. Every component of the neutralizer works in parallel.

As discussed in the previous section the immune algorithm has the following three steps:

1. Generation of Diversity
2. Establishment of Self-Tolenance
3. Memory of Non-Self

In accordance with these general steps, the neutralizer works in the following three phases.

1. Generation of recognizers

   At the first phase, the pairs of input and output signals
   $\{x_j(n), y_j(n), n = 1 \cdots, N_j\}$ must be generated.

   The plant to be controlled is assumed to be time invariant and stable.
   In that case, it is reasonable to suppose that an input signal with a finite duration produces an output signal with a finite duration.

   Therefore, $\{x_j(\cdot), y_j(\cdot)\}$ can be represented by a finite set of real numbers. However, if the characteristic of the plant were completely unknown, it would be difficult to prepare input-output pairs a priori. Some a priori knowledge of the plant must be assumed. In the simulation study in the following section, a model of plant is assumed to be known. If a model is available, given an input signal of a finite length, the corresponding output signal can be obtained by using the model. And the output is approximated by a signal of a finite length.

   It should be noted that the exact model of the plant is not required. Since the input-output pairs are changed randomly in progress of the adaptation, an approximate model is sufficient for the generation of the recognizers.

2. Establishment of Self-Tolerance

   In the control system, the error signal e is a sum of a signal proper to the control purpose and an additional signal due to disturbancecs.

   The neutralizer has to be trained at the initial stage of control operation so that it should be inactive to the meaningful siganal. This training can be done by simulations without disturbances if an model of the plant is available. If the simulation is impossible the real control operations must be carried out under conditions of small disturbances. For instance, if the control sytem is a servomechanism like robot manipulators for an industrial use, the training can be made during the operations with no loads or with small loads. Under the conditions the disturbances would be small.

3. Memory of Non-Self

   Recognizers, which is sensitive to meaningful signal, are deleted during the training period. And a recognizer which react on the disturbance- generated signal reproduces itself. Also recognizers inactive for longtime duration are deleted from the neutralizer. Therefor, the number of active recognizers increase during adaptation. Moreover, a small random variation is added to activated recognizer, so that more sensitive and effective recognizers are produced.

4.2 Simulation and performance of the disturbance neutralizer

The transfer functions of plant and controller for numerical simulations are; $P(s) = \frac{250}{s(s+130)}$, $C(s) = 40$, respectively. In this specific simulation, the control input $r(t)$ is assumed to be 0, hence only disturbance signals are imposed at the point d in Fig 2. Thus, the step of *Establishment of Self-Tolerance* is omitted for this simulation. When there are control signals, discrimination between the control signal and disturbance is critical. We further assume that the pair of recognition signal and neutralizing signal is given for those different agents. This pair is actually acquired during long evolutionary process in real biological system.

Disturbance that causes an error shown in Fig. 4 is imposed with period 200 step (1step = .005 sec). Fig. 5 shows time evolution of the error, and Fig. 6 shows that at 30000 step. As known from Figs. 5 and 6, the adaptive disturbance neutralizer successfully eliminate the disturbance. This means that there is an recognizer that corresponds to the imposed disturbance. The disturbance is also known to be neutralized gracefully from a period to period as step increases. This comes from the adaptation of recognizers, which is the result from adaptation of activated recognizers; higher affinity by higher rate of mutation in this case (as done in the step of *Memory of Non-self* in the immune algorithm).

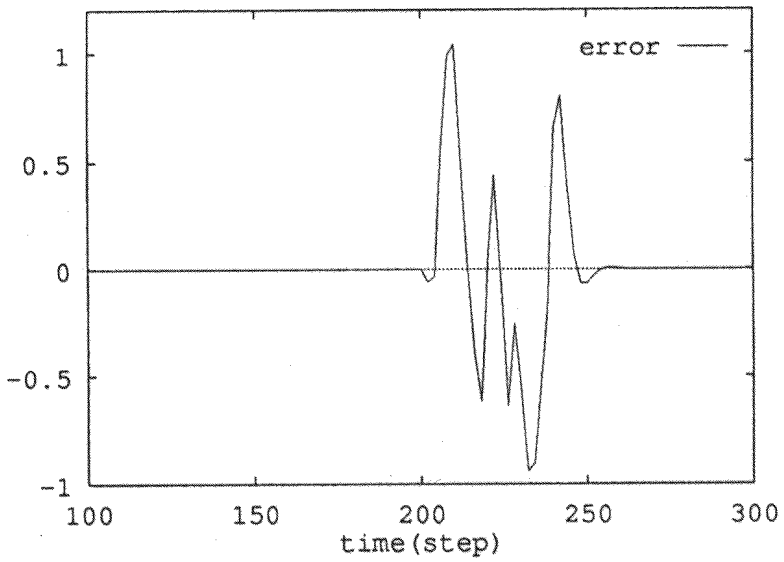

Figure 4: Error caused by the disturbance

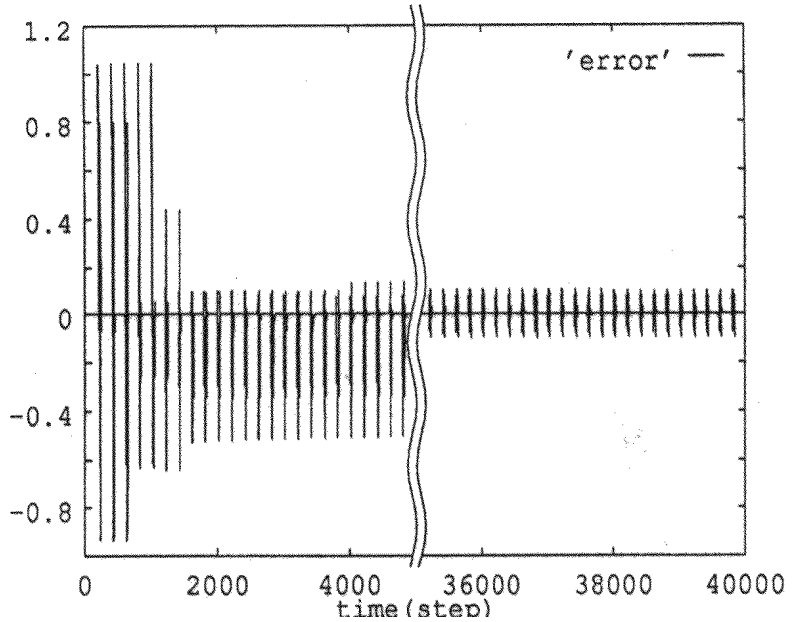

Figure 5: Time evolution of error

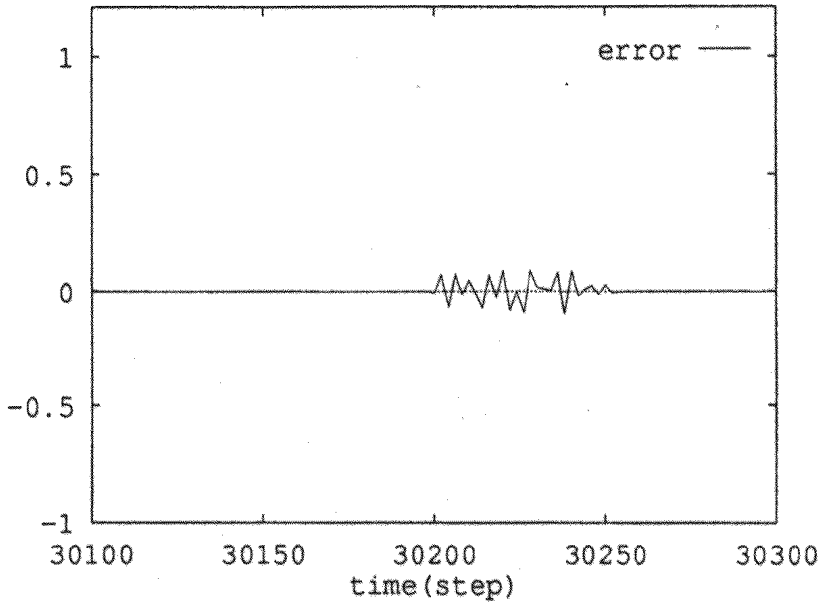

Figure 6: Time evolution of error at 30000 step

In another simulation, the responses to the initial (at 150 step as shown in Fig.7) and second (after 30000 step imposition of other disturbances as shown in Fig. 8) encounter are compared. The disturbance at secondary encounter is more effectively neutralized than that at the first encounter. This again comes from the adaptation of the recognizer; elongation of the life time in this case.

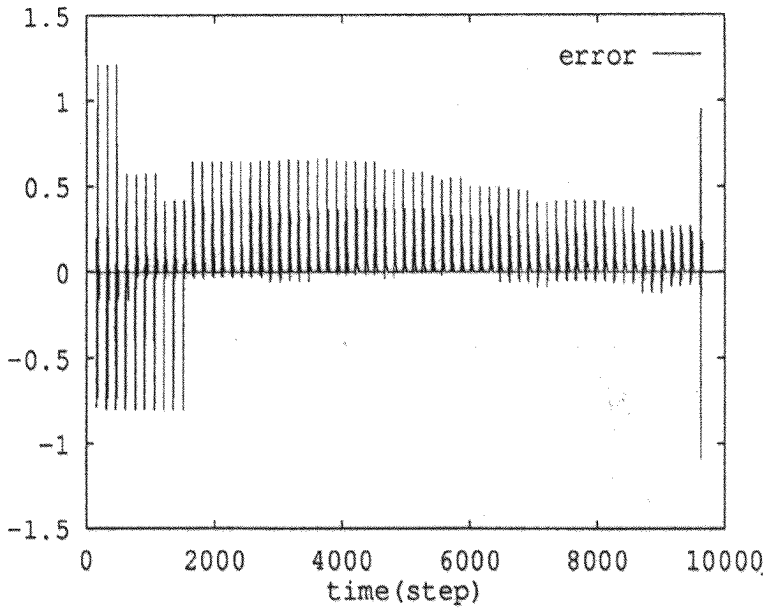

Figure 7: Response at the first encounter with the disturbance

In this simulation, one extreme of pure *agent-based* architecture is adopted. However, recognizers could communicate and cooperate in elimination of disturbance and memorizing disturbance pattern. For example, if the neutralizing signal can affect the other agents then it would be close to the *network-based* architecture. For the actual biological immune system, different types of cells communicate and cooperate extensively during elimination process as known under the name of *interleukin*[3]. The hybrid architecture should be elaborated for more sophisticated systems.

[3]Interleukin is a general term for molecules to communicate among leukocyte. Unlike the *network hypothesis*, they do not correspond to a specific antigen. Discovery and study of interleukin leads to dismissing the naive *idiotypic network* theory [4] that heavily depends on the specificity may be superficial. Later, they are found to react not only with leukocyte but with many other types of cells.

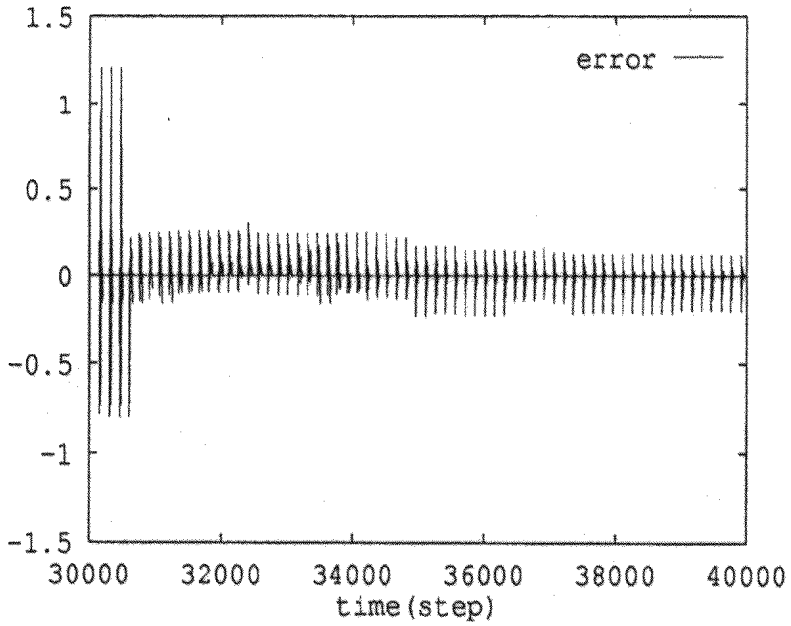

Figure 8: Response at the second encounter with the disturbance

5 Conclusion

A new information processing architecture extracted from immune systems is proposed. Two architectures; *network-based* architecture based on the network hypothesis and *agernt-based* architecture based on the local memory hypothesis are discussed. The architecture is neutral to both architecture, and promising for the system where the models of system itself and the environment are not available. The adaptive disturbance neutralizer is formalized by applying the *agent-based* architecture to a certain control system. By a simulation, it is demonstrated that the control mechanism with this architecture can actually eliminate disturbances and also it can eliminate more efficiently in secondary encounter with the same disturbances.

The architecture should be elaborated and refined. Agent-based and network-based architecture should be combined for future research. Further, the problem of how initial recognizers should be built remained.

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References

[1] S. Levin, Eds, *System Theories in Immunology*, in Lecture Notes in Biomathematics, Springer-Verlag, 1978.

[2] P. H. Richter, "Complexity and Regulation of the Immune System: The Network Approach," in *Proc. Working Conf. on System Theory in Immunology,* pp. 219-227, Rome, Italy, May 1978 (Springer-Verlag, New York).

[3] R. R. Mohler, C. Bruni, and A. Gandolfi, "A Systems Approach to Immunology", *Proc. of the IEEE*, Vol. 68, No. 8, pp. 964-990, August, 1980.

[4] N. K. Jerne, "The Immune System" *Sci. Am.* Vol. 229, No.1, pp. 52-60, 1973.

[5] G. W. Hoffman, "A Neural Network Model Based on the Analogy with Immune System," *J. Theor. Biol.*, 122, pp.33-67, 1986.

[6] J. D. Farmer, N. H. Packard, and A. S. Perelson, "The Immune Systems, Adaptation, and Machine Learning" *Physica,* 22D, 187, 1986.

[7] H. Atlan and I. R. Cohen, Eds, *Theories of Immune Networks*, Springer-Verlag, 1989.

[8] H. Bersisni and F.J. Varela, "The Immune Recruitment Mechanism: A Selective Evolutionary Strategy" *Proc. ICGA 91*, 1991.

[9] Y. Ishida, " Fully Distributed Diagnosis by PDP Learning Algorithm: Towards Immune Network PDP Model", *Proc. of IJCNN 90*, San Diego, 1990.

[10] Y. Ishida and F. Mizessyn, "Learning Algorithms on Immune Network Model: Application to Sensor Diagnosis" *Proc. IJCNN 92*, Bei Jing, pp. 33-38, 1992.

[11] Z. Grossman, "The Concept of Idiotypic Network: Deficient or Premature?" in *Theories of Immune Networks*, H. Atlan and I.R.Cohen Eds, Springer-Verlag, 1989.

[12] W.M. Wonham, *Linear Multivariable Control -A Geometric Approach-*, Springer-Verlag, 1970.

[13] G. Feng, and M. Palaniswami, "Continuous time indirect adaptive control with disturbance rejection", *Systems & Control Letters* 18, 211-215, 1992.