Multi-Robot Cooperation using Immune Network with Memory

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***Abstract*— In this paper, basic biological immune systems and their responses to external elements to maintain an organism's health state are described. The relationship between immune systems and multi-robot systems are also discussed. Our proposed algorithm is based on immune network theories that have many similarities with the multi-robot systems domain. The paper describes a memory-based immune network that enhance a robot's action-selection process and can obtain an overall a quick group response. The algorithm which is named as *Immune Network T-cell-regulated—with Memory* (INT-M) is applied to the dog and sheep scenario. Simulation experiments were conducted on the Player/Stage platform and experimental results are presented.**

I. INTRODUCTION

Usually mobile robots need to interact and engage with one another in order to achieve assigned tasks more efficiently. These autonomous multi-robot systems would be highly beneficial in assisting humans to complete suitable tasks. In such systems, distributed intelligence is highly needed in the team whereby decisions are processed in each individual robots [1]. Furthermore, these robots would need to have the mechanism to cooperate so that they would achieve the assigned task [2].

Biological systems are examples of distributed information processing that are capable of solving problems in living organisms in a distributed manner. Some of these biological systems have neural networks in the brain that is capable of processing information through impulses at the synapses, genetic systems in constructing the organism genes and immune systems which protect and maintain the homeostatic state of the living organism. Biological immune systems are particularly interesting, not only because they have no central processing but also exhibit cooperative capability among the antibodies in maintaining the internal stable environment of the body.

This leads to the advances in research on Artificial Immune Systems (AIS) and the application of AIS in engineering fields particularly in Multi-Robot Systems (MRS) domain [1]–[3]. Situations faced by multi-robot systems require real-time processing and response. Furthermore, such situations would also require these systems to be robust to changes in the environment and some unexpected events, such as failure of robots in the team. Thus, mimicking the biological immune system is appropriate.

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This paper proposes a memory-enhanced immune system algorithm to achieve cooperative behavior in a team of robots. Using the algorithm inspired by the immune network theory, the robots have the capability of performing their mission in a dynamically changing environment. The proposed algorithm is applied to the dog and sheep scenario [3], [4]. Simulation experiments are arranged to investigate the proposed algorithm using the above scenario.

This section explains the principle of the biological immune response and the Idiotypic Network Hypothesis which describe the cooperative behavior achieved by immune systems in vertebrate organisms. This is followed by the generic relation between immune systems and multi-robot systems.

A. Biological Immune Systems

Immune system is a system that eliminates foreign substances from an organism's body. These foreign substances such as bacteria, fungi or virus cells that can harm the host are called pathogens. When such substance activates an immune response it is called *antigen*, which stimulates the system's antibody generation. Each antigen has a unique set of identification on its surface called *epitope*. These antigenic determinants are where the host's antibodies would attach to by using their paratope, as shown in Fig. 1. *Antibodies* are cells in the immune system that kill antigens in order to maintain the host homeostatic state—i.e. balancing the body's health status.

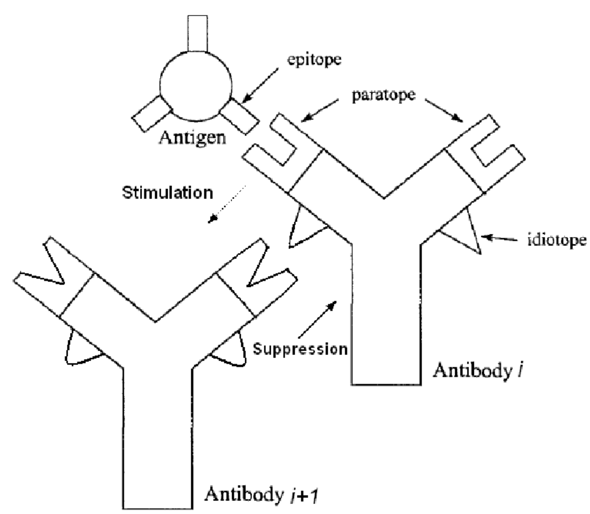

Fig. 1. Antigen-antibody binding and Jerne's Idiotypic Network Theory

The immune system can be divided into two general categories, innate immunity and adaptive immunity. Innate immunity is the first line of defense of the immune system. Generic pathogens that can be recognized and killed by the innate immunity cells would not be able to harm the host further. However, certain disease carrying antigens would bypass this defense mechanism because the innate immunity does not adapt to antigens that originate from various types of illnesses. The adaptive immunity would then play its role through the use of *lymphocytes* which are generally known as white blood cells. Lymphocytes have two main types, *T-cells* that mainly help in recognizing antigen cells and *B-cells* that mainly produce antibodies to fight specific antigens. In humans, T-cells are primarily produced in the thymus while B-cells are produced in bone marrows. These innate and adaptive immune responses make up effective and important defense mechanism for living organisms.

B. Immune Response

The immune response basically can be viewed in six phases of recognition and activation, as seen in Fig. 2. Pathogen is digested by Antigen Presenting Cells (*APCs*) where it is broken down into *peptides* [5]. These peptides will then bind to Major Histocompatibility Complex (*MHC*) molecules, then presented on the APC surface. T-cells recognize these different APC receptors and thus become activated. They divide and release *lymphokines* that transmit chemical signals to stimulate other immune system components to take action. B-cells would then travel to the affected area and be able to recognize the antigen. This would activate the B-cells which then mature into *plasma cells*. Plasma cells are the ones which release specific antibody molecules that neutralize the particular pathogens.

This immune response cycle results in the host's immunity against the antigen which triggers it, thus having protection in future attacks [5]. Prominent characteristics of the immune system is that there is no central control of the lymphocytes in fighting antigens that invade the host and the system's adaptability in responding to various kind of antigens. The B-cells cooperatively merge at the affected area and produce appropriate antibodies for that particular situation. This phase of immune response exhibits cooperative behavior of the related cells.

C. Idiotypic Network Hypothesis

Studies in immunology have suggested that antibodies are not isolated but they 'communicate' with each other. Each type of antibody has its specific *idiotope*, an antigen determinant as shown in Fig. 1. Jerne who is an immunologist proposed the Idiotypic Network Hypothesis (also known as Idiotypic Network Theory) which views the immune system as a large-scale closed system consisting of interaction of various lymphocytes (i.e. B-cells) [6] . Referring to Fig. 1, idiotope of antibody i stimulates antibody $i+1$ through its paratope. Antibody $i+1$ views that idiotope (belonging to antibody i) simultaneously as an antigen. Thus, antibody i is suppressed by antibody $i+1$. These mutual stimulation and suppression chains between antibodies form a controlling mechanism for the immune response [5].

Farmer et al. in [7] proposed differential equations of Jerne's idiotypic network theory. These equations consist of antibodies' stimulus and suppression terms, antigen-antibody affinity, and cell's natural mortality rate [7]. This large-scale closed system interaction is the main mechanism that can be used for cooperation of multi-robot systems.

D. Immune Systems and MRS

The relationship of the immune systems with multi-robot systems is evident where obstacles, robots and their responses are antigens, B-cells and antibodies respectively. Table I lists the obvious parallel of MRS and immune systems terminologies.

TABLE I
IMMUNE SYSTEMS AND MRS RELATIONSHIP

Immune Systems	**Multi-Robot Systems**
B-cell	Robot
Antigen	Robot's Environment
Antibody	Robot's action
T-cell	Control parameter
Plasma cell	Excellent robot
Inactivated cell	Inferior robot
Immune network	Robots interaction
Stimulus	Adequate robot stimulation
Suppression	Inadequate robot stimulation

Immune network theory as previously described is suitable as a basis for emulating cooperative behavior in a multi-robot environment. This is because the immune network uses affinity measures that are dependent on other cells concentration and location in determining the next action. Other than that, multi-robot systems require recognition ability of obstacles and other robots, which is parallel to the immune system recognition and activation phase of an immune response. Obviously, in immune network the processing of information is done in real-time and in a distributed manner—as what a multi-robot system requires.

II. IMMUNE NETWORK BASED MULTI-ROBOT COOPERATION

Sun et al. in [8] have proposed a model based on Farmer's immune network equation that involves T-cells as control parameter which provides adaptation ability in group behavior.

The group control or coordination phase is done in a distributed manner via local communication between nearby robots. When a robot encounters other robot and both have the same or similar strategy, this strategy is stimulated; if not, the strategy is suppressed. This facilitates the group to self-organize towards a common action which is optimal for the local environment. If a robot is stimulated beyond a certain threshold—which makes it an excellent robot, its behavior is regarded as adequate in the system such that it can transmit its strategy to other inferior robots. This is a metaphor of the plasma cell in the biological immune systems.

The advantage of adding the T-cell model is that the system adapts quickly to the environment by recovery of antibody concentration to the initial state, when antigens

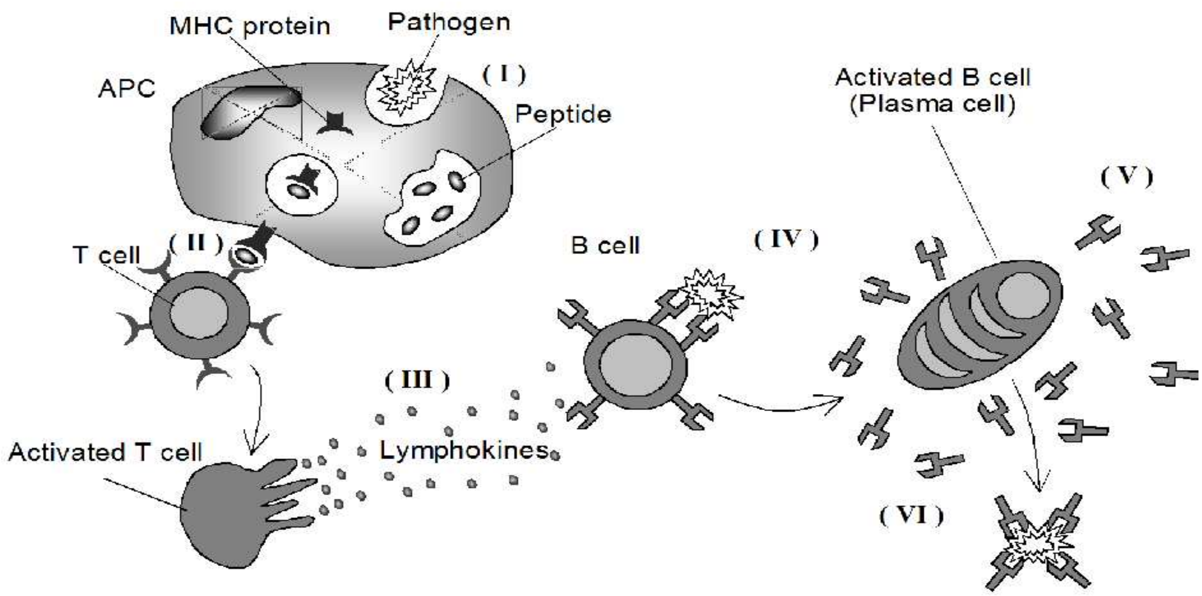

Fig. 2. Basic biological immune systems response [5]

have successfully been removed. Thus, the system is more adaptable to environmental changes.

Our proposed approach is based on [8], with the extension of memory ability so that quick responses can be achieved in certain relevant situation.

III. IMMUNE NETWORK WITH MEMORY

In biological immune response, there is a Clonal Selection process, whereby various B-cells try to identify the antigen. Once the appropriate B-cell is selected, it is activated and multiplied (i.e. proliferate) so that adequate immune response could be mounted later. The activated B-cells will proliferate and differentiate into Plasma cells that will secrete specific antibodies and memory cells which will be in the host body for quite a long time [5]. These memory cells will act as catalysts in mounting a quick immune response to the same antigen in the future.

A. The INT-M Model

In order to improve the approach by [8], a specific memory mechanism is proposed in order to retain the appropriate action for relevant environment condition. This mechanism is introduced when the newly sensed environment is similar to the previous environment. Thus, a quick action-selection process can be executed without the need of re-evaluating the new situation.

The approach is aptly named as *Immune Network T-cell-regulated—with Memory* (INT-M) as it involves modelling the memory part of the biological immune systems. The general algorithm is shown in algorithm 1 which is an extension of [8]. The algorithm being displayed is for each robot in the group, and uses (2), (3) and (4).

$$\sum_{j=0}^{N-1} (m_{ij} - m_{ji})\, s_j\,(t-1) \tag{1}$$

$$S_i\,(t) = S_i\,(t-1) + \left(\alpha \frac{\text{Equation(1)}}{N} + \beta g_i - c_i\,(t-1) - k_i\right) s_i\,(t-1) \tag{2}$$

$$s_i\,(t) = \frac{1}{1+\exp\,(0.5 - S_i\,(t))} \tag{3}$$

$$c_i\,(t) = \eta\,(1 - g_i\,(t))\,S_i\,(t) \tag{4}$$

In (2) and (3), $S_i(t)$ is the stimulus value of antibody i where $i, j = 0 \ldots N$, N is the number of antibody types. m_{ij} is the mutual stimulus of antibody i and j, which is referred to in Table II. g_i is the affinity of antibody i and antigen, which can arbitrarily be assigned using a function. $s_i(t)$ is the concentration of antibody i. The difference with Farmer et al. immune network equation in [7] is that $s_j(t)$ is not the concentration of self-antibody, but that of other robot's antibody obtained by communication.

TABLE II
MUTUAL STIMULUS COEFFICIENT, m_{ij}

robot i \ robot j	$\mathbf{Ab_0}$	$\mathbf{Ab_1}$	$\mathbf{Ab_2}$	$\mathbf{Ab_3}$
Aggregation, $\mathbf{Ab_0}$	1	-0.4	-0.2	-0.4
Search, $\mathbf{Ab_1}$	-0.4	1	-0.4	-0.2
Dispersion, $\mathbf{Ab_2}$	-0.2	-0.4	1	-0.4
Homing, $\mathbf{Ab_3}$	-0.4	-0.2	-0.4	1

Equation (4) is the T-cell model whereby $c_i(t)$ is the concentration of T-cell which controls the concentration of antibody i. α, β, and η are constants, whereby α and β are parameters of response rate of other robot and the environment (antigen) respectively. In biological immune systems, helper T-cells activate B-cells when antigen invades, and suppressor T-cells prevent the activation of B-cells when the antigen has been eliminated thus ensuring that the system adapts quickly to the environment by recovery of antibody concentration to the initial state.

Equations (5) and (6) are the functions and its corresponding values for the upper ($\overline{\tau}$) and lower ($\underline{\tau}$) thresholds in determining whether a robot becomes an excellent (i.e. plasma cell) or an inferior (i.e. inactivated cell) robot.

$$\overline{\tau} = \frac{1}{1 + e^{-0.5}} = 0.622 \tag{5}$$

$$\underline{\tau} = \frac{1}{1 + e^{0.5}} = 0.378 \tag{6}$$

IV. SIMULATION

In this research we investigate shepherding behavior of robots. Shepherding behavior is similar to a flocking behavior but having agents/robots outside of the flock guiding or controlling the members [9]. Fig. 3 shows the screenshot of the dog and sheep scenario.

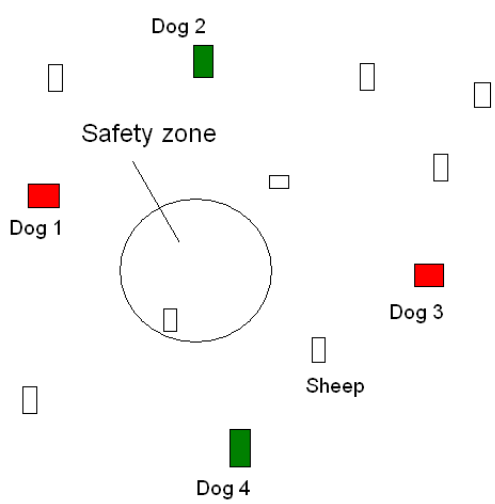

Fig. 3. The Dog and Sheep problem environment

In a dog and sheep problem, a few dogs try to guide a few sheep to the grazing site (also called the safety zone) without going beyond the borders [4]. Dogs are required to cooperate in shepherding the sheep which are moving away from the dogs or wandering randomly inside the area. The objective is to prevent the sheep from going out of the grazing site while having partial information of what is happening in the area.

This problem is highly dynamic and obviously requires the robots to have real-time processing of partial information of the environment. The robot dogs use the proposed immune-inspired approach in cooperating with one another while the robot sheep have basic avoidance and flocking behaviors.

The proposed approach as described in algorithm 1 is applied to the dog and sheep problem and adjusted where necessary. The Player/Stage simulation platform [10] on a Fedora Core 6 Linux operating system is being used to test

Algorithm 1 Immune Network T-cell-regulated—with Memory (INT-M)

Require: $t = 0$, $S_i(0) = s_i(0) = 0.5$ for $i = 0 \dots N-1$, N is number of actions
Ensure: retain previous Ab if robot is not inferior within similar environment, execute Ab_{max}

```
Ab_max ← Ab_1
robot ← inferior
environment ← similar

loop
  Execute Ab_max

  {robot is activated (normal) or excellent}
  if robot ≠ inferior then
    {environment sensed is similar to previous}
    if g_i(t) ≈ g_i(t − 1) then
      S_i(t) ← S_i(t − 1)
      s_i(t) ← s_i(t − 1)
      c_i(t) ← c_i(t − 1)
    else
      environment ← changed
    end if
  end if

  {robot is inferior or environment has changed}
  if (robot=inferior)||(environment=changed) then
    for i ← 0 to N − 1 do
      Calculate S_i(t)
      Calculate s_i(t)
      Calculate c_i(t)
    end for

    if S_i(t) > τ̄ then
      robot ← excellent
    else if S_i(t) < τ̲ then
      robot ← inferior
      if robot encounter robot_excellent then
        for all i do
          receive Ab_i
          renew s_i(t)
        end for
      end if
    end if
  end if

  if Ab_i has max(s_i(t)) then
    Ab_max ← Ab_i
  end if

  t ← t + 1
end loop
```

the proposed algorithm. Fig. 4 shows a sample screenshot of the simulation platform. Experimental data is currently being collected to analyze the behaviors of the simulated robots.

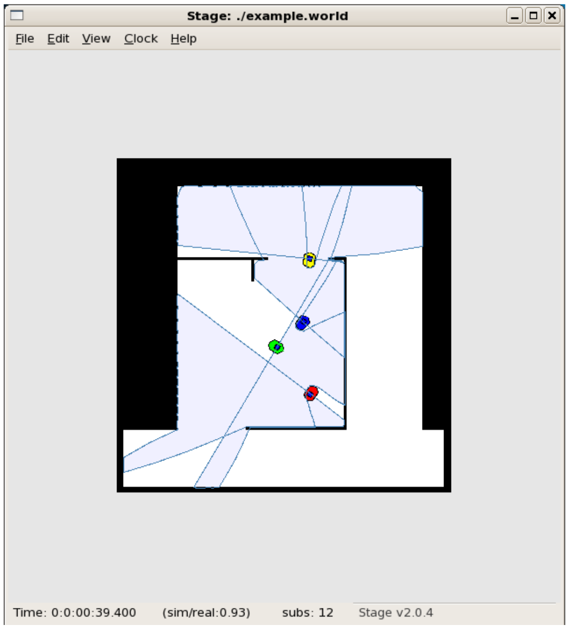

Fig. 4. The Player/Stage simulation platform

A distinct part of this study is that we are looking into the memory-based immune network cooperation approach by the robots (i.e. dogs) in maintaining the herd (i.e. sheep). This utilizes the advantage of memory in the action-selection phase and affects the resulting dynamic behavior of both the robot dogs and the robot sheep.

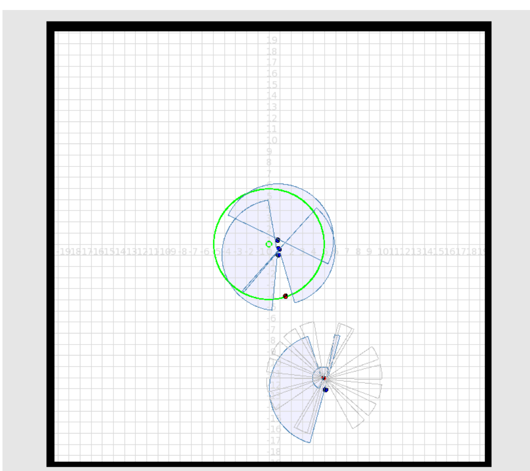

Fig. 5. The simulation experiment—involving 2 sheep

Fig. 5 is a snapshot of one of the experiment done that shows the limited behavior of local shepherding. Other robot dogs do not sense the sheep that is outside of the grazing site. The one robot dog that is chasing the particular sheep is doing all the shepherding, which is not optimal as a group.

V. RESULTS

A. Experimental Setup

The experiments are done for shepherding 2, 5 and 8 numbers of sheep. The shepherding behaviors are the immune-based and the local shepherding behavior. In local shepherding, the robot dogs will only chase the sheep within its range and do not have any cooperation mechanism. The range for the robot dogs are set to 5 meters for forward sight (i.e. laser) and 20 meters for emulating sense of hearing.

The field is constructed of a walled field with the size of 40 meters each side. The grazing site is situated at the center with a radius of 5 meters and each sheep that have entered it will stop. Each experiment is limited to a limit of 5 minutes and it is done for 3 times and the average values are then calculated.

B. Discussions

The performance is measured on two aspects. The average time of the first sheep that is shepherd into the grazing site (which is known as Time for Completion), and also the number of sheep left in the field (which is known as Incomplete Task) after the maximum time is up.

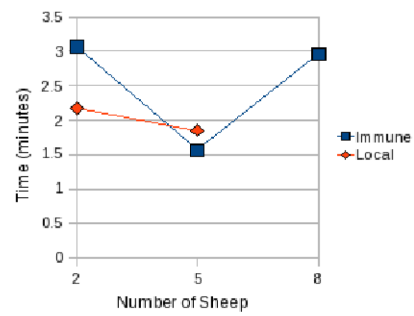

Fig. 6. Average Time for Completion

The average time for completion is shown in Fig. 6, where the point for Local Behavior with 8 sheep is not plotted because all sheep are unable to be sheperd into the grazing site by using the local shepherding approach. The result shows that the immune-based approach can scale better compared to the local behavior.

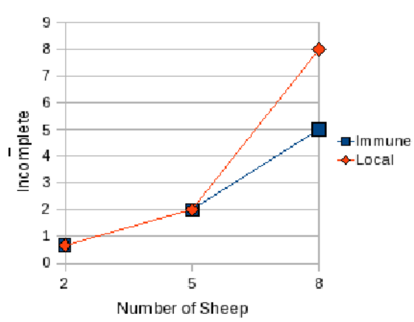

Fig. 7. Average Incomplete Tasks

Another important performance to consider is the average number of incomplete tasks that signify the ability to maintain the balance of the overall goal of shepherding all the sheep and also completing it in a short time. Fig. 7 shows that the immune-based approach has lower average incomplete task as the number of sheep gets larger, meanwhile the local shepherding totally fail when the number of sheep is set to eight. This signify that the immune network cooperation in shepherding can gain better completion time without sacrificing the overall goal (i.e. having low rate of incomplete tasks).

VI. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In this paper a memory-based immune system inspired approach for cooperation in multi-robot systems has been proposed. We have described the basic concepts and mechanisms of biological immune systems, and argued that the immune network is a suitable analogy for multi-robot cooperation problem. We have also proposed a multi-robot cooperation algorithm—the INT-M model, and applied it to the dog-sheep test scenario. An experimental simulation environment has been setup to evaluate the proposed approach and algorithm.

B. Future Works

The approach will be extended to other application domains which require several agents (robots) to work cooperatively in a distributed way in a dynamic environment.

VII. ACKNOWLEDGMENTS

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