A Refined Immune Systems Inspired Model for Multi-Robot Shepherding

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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. The proposed algorithm is based on immune network theories that have many similarities with the multi-robot systems domain. The paper describes a refinement of the memory-based immune network that enhances a robot's action-selection process. The refined model; which is based on the *Immune Network T-cell-regulated—with Memory* (INT-M) model; is applied onto the dog and sheep scenario. The refinements involves the low-level behaviors of the robot dogs, namely *Shepherds' Formation* and *Shepherds' Approach*. The shepherds would form a line behind the group of sheep and also obey a safe zone of each sheep, thus achieving better control of the flock. Simulation experiments are conducted on the Player/Stage platform.**

***Keywords*-immune systems; multi-robot; shepherding; immune network;**

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.

This paper proposes a refinement upon the memory-enhanced immune system algorithm to achieve better shepherding behavior in a team of multiple shepherds. 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 refined algorithm is applied to the dog and sheep scenario [3], [4]. Simulation experiments are arranged to investigate the refinements performance using the stated scenario.

II. Inspiration from Immunology

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.

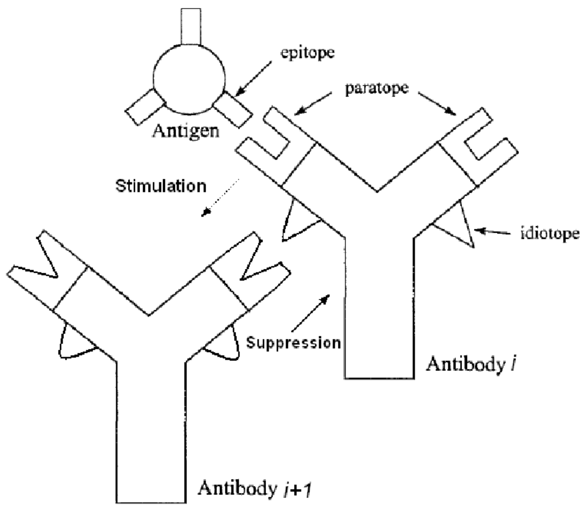

Fig. 1. Antigen-antibody binding and Jerne's Idiotypic Network Theory

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 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

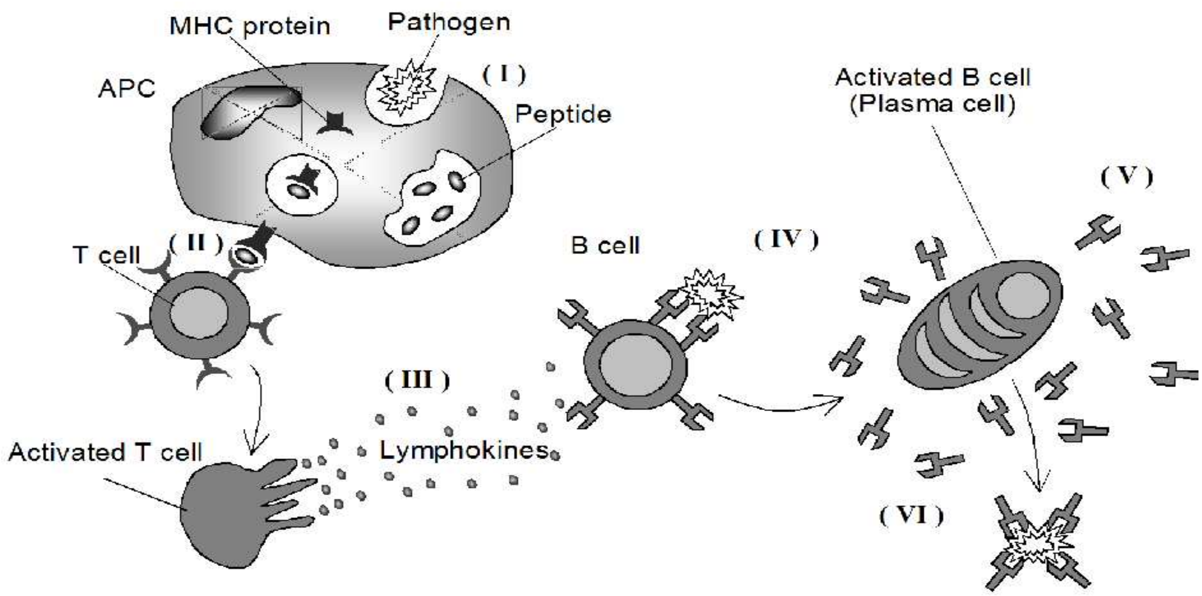

Fig. 2. Basic biological immune systems response [5]

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.

III. Immune Network Inspired Multi-Robot Shepherding

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

A. The INT-M Model

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.

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 modeling the memory part of the biological immune systems as detailed in [9]. The general algorithm is shown in Fig. 3 which is an extension of [8]. The algorithm being displayed is for each robot in the group, and uses (2), (3) and (4).

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

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

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

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

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 explained in [9]. 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.

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. The respective values of 0.622 and 0.378 are 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 [9].

B. The INT-M Refinement

Referring to [10], multiple shepherds pose a few underlying problems regarding the interaction between the shepherds and the flock. The proposed refinement of the INT-M model is focused only on the *Shepherds' Formation* and *Shepherds' Approach* aspects. This refinement is then applied onto the dog and sheep scenario.

The formation involves the robot dogs to line-up behind the group of sheep so that the flock can be better controlled. The approach is also refined as in when a robot dog move towards a sheep it will obey the safe zone of that sheep, so that the sheep would not be influenced by the incoming dog. This will achieve a lower flock separation occurrences, thereby having better shepherding behavior. Fig. 4 is the depiction of the proposed refinement of the model by having the robot dogs forming a line behind the group of sheep.

IV. The Test Scenario

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 [11].

A distinct part of this study is that we are looking into the refined low-level behavior of the memory-based immune network cooperation approach by the robots (i.e. dogs) in maintaining the herd (i.e. sheep). This utilizes better shepherding control in addition to the advantage of memory in the action-selection phase.

A. Dog-Sheep Scenario

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

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

$Ab_{max} \leftarrow Ab_1$
robot $\leftarrow$ inferior
environment $\leftarrow$ similar

loop
  Execute Ab_{max}

  {robot is activated (normal) or excellent}
  if robot $\neq$ inferior **then**
    {environment sensed is *similar* to previous}
    if $g_i(t) \approx g_i(t-1)$ **then**
      $S_i(t) \leftarrow S_i(t-1)$
      $s_i(t) \leftarrow s_i(t-1)$
      $c_i(t) \leftarrow c_i(t-1)$
    else
      environment $\leftarrow$ changed
    end if
  end if

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

    if $S_i(t) > \overline{\tau}$ **then**
      robot $\leftarrow$ excellent
    else if $S_i(t) < \underline{\tau}$ **then**
      robot $\leftarrow$ 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**
    $Ab_{max} \leftarrow Ab_i$
  end if

  $t \leftarrow t+1$
end loop

Fig. 3. Immune Network T-cell-regulated—with Memory (INT-M)

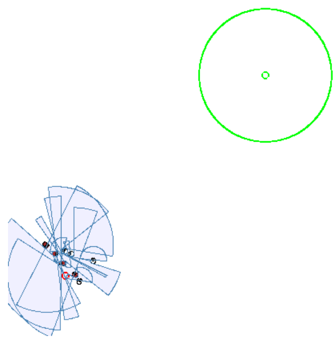

Fig. 4. The robot dogs lining-up, the refinement of low-level shepherding behavior

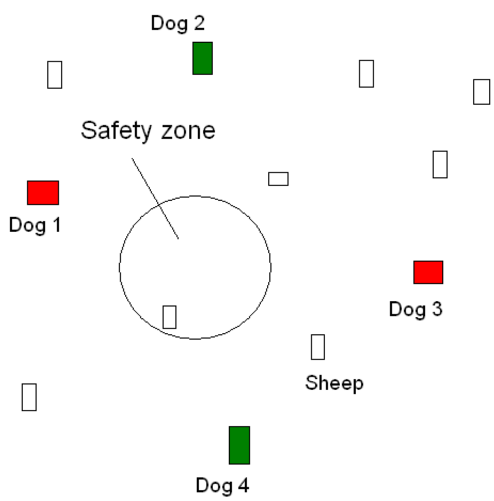

Fig. 5. The Dog and Sheep problem environment

having partial information of what is happening in the area. Fig. 5 shows the screen-shot of the dog and sheep scenario.

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.

B. Simulation Setup

The proposed approach as described in Fig. 3 together with the refinements is applied to the dog and sheep problem and adjusted where necessary. The Player/Stage simulation platform [12] on a Fedora 9 Linux operating system is being used to test the refined model. Fig. 6 shows a sample screen-shot of the simulation platform. Experimental data had been collected to analyze the behaviors of the simulated robots.

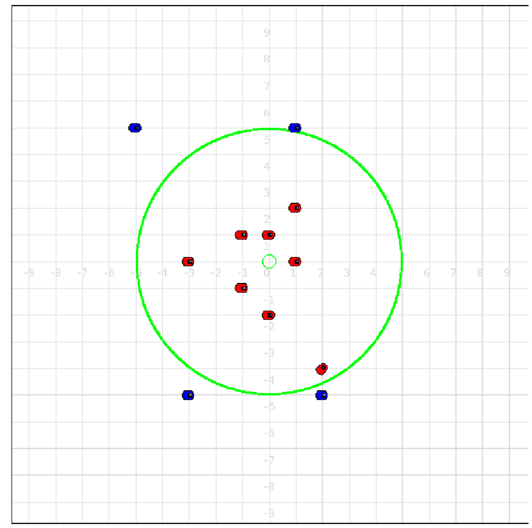

Fig. 6. The Player/Stage simulation platform with the dog and sheep scenario

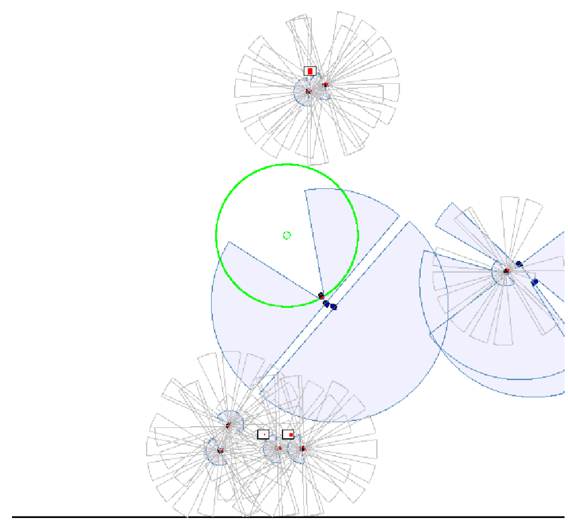

Fig. 7. The simulation experiment—involving 8 sheep and 4 dogs using immune-based cooperation

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 several times and the average values are calculated. Fig. 7 is a snapshot of the simulation that shows the immune-based shepherding whereby the shepherds are cooperatively herding specific sheep that they have been assigned.

V. Performance Criteria

The performance can mainly be measured on two aspects. The average distance of the flock that is shepherd into the grazing site (which is known as Average Distance to Origin), and also the number of sheep left in the field (which is known as Incomplete Task) after the maximum time is up. The average number of incomplete tasks criterion signifies the ability to maintain the balance of the overall goal of shepherding all the sheep and also completing it within the specified time.

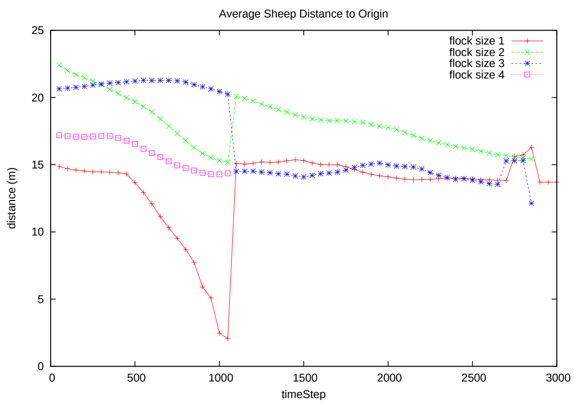

Fig. 8. Average Distance to Origin

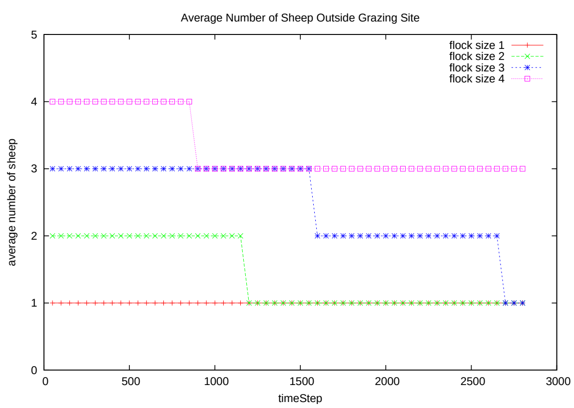

Fig. 9. Average Incomplete Tasks

Fig. 8 shows the average distance of the flock (in relation to the origin) over each time-step. There are four flock sizes in the experiment — from one sheep up until four sheep in a herd. The figure shows that in average the group of sheep is able to be contained within the flock.

Fig. 9 shows the average number of sheep still outside of the grazing site over each time-step. The figure suggests that in average there will at least be one sheep that can be shepherd into the grazing site. In general, flocks of size 3 can achieve lower task incompletion rate within the time limit. On the other hand, flocks with 4 sheep display quicker response that might indicate a trend. This may require further investigation.

VI. Conclusion

In this paper refinement of the memory-based immune system inspired approach for shepherding 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 refinements on the multi-robot cooperation algorithm—the INT-M model, and applied it to the dog-sheep test scenario. Simulation experiments had been carried out to evaluate the proposed approach and algorithm.

VII. 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. It will be further implemented on the e-puck robots to obtain the algorithm performance in real world situation [13].

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