Cognitive Maps in Swarm Robots for the Mine Detection Application*

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Abstract - Navigation based on cognition is seen in many instances in the animal community. Maps are very useful for navigation in unknown and complex environments. User defined and preinstalled maps can be very useful in navigation in complex environments, while adaptively built maps become very essential in unknown environments. Intelligence is bestowed in the effective utilization of data to produce decisions. In the case of navigation, intelligence is seen when information collected en-route from a source to a destination is used judiciously in reaching the destination. In this paper we deal with the foraging of a piece of terrain as a process of navigation. The application here is mine detection. Mines are placed over a field at unknown locations and swarm intelligence based agents are deployed for demining them. The efficiency of the demining process is measured in terms of the quickness with which they can clear the mines and the assurance that the minefield is clear of mines at the end of the process. Simulation results acknowledging the performance under different working conditions of the swarm robots are presented. In an endeavor to substantiate our claims in simulation we decided to build swarm robots performing the task on an artificially developed environment.

Keywords: Swarm intelligence, mine detection, ant colonies, foraging, cognitive maps, visual cues, and swarm robots.

1 Introduction

Swarm Intelligence concepts have captivated the interests of researchers mainly in collective robotics, optimization problems, and communication networks (routing) etc [2, 8, 10, 11]. This research focuses on the application of swarm intelligence to the problem of mine detection. The process of mine detection comprises of the sub-tasks such as foraging for mines over the mine field, demining the mines by some means and assuring that the mine field is clear of mines at the end of the task. In this paper, we try to capture the functionalities of the swarms in carrying out the task on simulation and also to demonstrate it by building robots to perform the task physically. Foraging, which is defined as the act of searching for mines on the field largely affects the performance of the mine detection task [2, 8, 10, 11]. We target an ant colony based swarm intelligence technique for the demining process. Heuristics based on cognitive maps in ants is used to achieve this task. The ants do the task effectively when they are able to assure that the minefield is clear of the mines within the least possible time.

One of the important areas of research in swarm intelligence is heuristics arising from natural phenomenon. One of the key solutions to solving combinatorial optimization problems is non-deterministic heuristics. Group of individual interacting agents exhibit heuristics in solving a common task presented to them at the colony level. Natural heuristics can be observed in the animal kingdom where colony level existence of a particular species is seen. Examples can be group of insects, herds, and ant colonies. Some of the features seen in heuristics in nature are non-determinism, multiple interaction, and evolution [2, 8, 10]. Adaptivity or selections of the best and mutation or random fluctuation are two features prominently seen in natural systems [2, 8, 10]. Optimization is taken care by selectivity and non-determinism is a result of randomness in the system.

Section II describes the general swarms in nature and their collective intelligence manifestations. We deal with ant colonies, which we have used extensively for our analysis. Section III highlights the foraging techniques found in ant colonies. This section discusses the concept of cognitive maps used in ant foraging. Section IV

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discusses the mine detection problem, the assumptions we have made for our simulations, and the strategies we have adopted for solving the problem. The concluding section tabulates and analyzes the results we obtained during simulation of the mine detection task with various foraging strategies. Comparative performance was carried out to evaluate the performance of ants equipped with cognitive memory.

2 Swarms in Nature

Swarms are a class of entities found in nature which specialize in mutual cooperation among them in executing their routine needs and roles. Swarm Intelligence is a new computational and behavioral metaphor for solving distributed problems; it is based on the principles underlying the behavior of natural systems consisting of many agents, such as ant colonies and bird flocks [8, 9, 12, 15]. The approach emphasizes distributedness, direct or indirect interactions among relatively simple agents, flexibility, and robustness. Applications include optimization algorithms, communications networks, and robotics [2].

Ant colonies, which show strong level of colonial intelligence, are typical objects of the swarm family. Typical swarm intelligence phenomenon such as self-organization, emergent behavior, and stigmergy are seen in ant colonies. Positive and negative feedback mechanisms help a system stabilize at the colony to suit varying environmental conditions. These mechanisms result in adaptiveness in the system and are referred to as self-organizing mechanisms. Multiple interactions produced by individuals in a colony result in the phenomenon of emergent behavior [2, 8, 10]. This is seen, when a group of agents that has been defined with a set of simple rules interact among themselves to produce complex patterns. Stigmergy is the phenomenon that produces actions and reactions without direct mutual interactions. The environment is generally where information is embedded and retrieved to cause actions and reactions.

The traditional difference between artificial intelligence researchers and naturalists is that naturalists study animal or human behavior to determine the nature of information storage and processing in them. In the case of artificial intelligence researchers computational issues are important. Ant colony based heuristics is used to model behaviors for the swarm robots in our research. There are complex tasks, which are faced by the ants as a colony in their life style. Natural heuristics are evident in the coordination shown by the ants in executing tasks such as food gathering, nest building, brood sorting and colony level defense. Researchers have shown that ants tend to forage the terrain near to the nest for food. They devise their strategy based on information obtained from cognitive maps [8, 10]. Cognitive maps are orientation diagrams of important landmarks on the terrain. Based on these they utilize certain heuristic methods to devise their foraging strategies. Foraging is defined to be the search of a piece of terrain in order to find food utilizing minimal resources [2, 8].

3 Cognitive Maps

Self-organization in neurons exhibits similar characteristics to swarms in many respects. Communication can be defined as an action of an entity in a group of entities that can influence the probability pattern in another entity in a manner conducive to both. Actions that have the ability to influence a group of individuals are called group communications or collective communication. A fine example of group communication is stigmergy where individual's actions are produced on the environment. These actions act as a medium of information conveyance as against direct communication found in other sophisticated mechanisms. Many factors such as pheromone deposition, cognitive map constructions are brought into effect when group or collective communication has to be exhibited. Direct actions involve the observance of individual agents or entities producing them, which generally are not huge or complex. Collective communication on the other hand involves the collection and observation of large data and their statistical processing. The observer in numerous interpretations can manipulate the inference from this collected data. Often the results produced, generally called the reactions to the collective actions, depends mostly on initial conditions and behavioral assumptions. It is difficult to determine which behavioral actions are required to effect a particular reaction and which are sufficient [9, 10, 15]. What we would like to show in our experiments is that numerical analyses of the actions are possible and that there are similarities between the underlying dynamics and the emergent properties of the ants and its cognitive map construction and organization.

Cognitive maps are mental representations of physical observations on a terrain [10, 15]. Cognitive maps can be used in navigation by most of the living forms. Cognitive maps form an assorted means of information storage, which can be utilized in navigation and path finding in most organisms. Two important themes occur in this information representation of cognitive maps; (i) a notion of global representation and (ii) local representation [4, 9, 15]. Global representations of data relate to cognitive ideas and information formed which can aid in fulfilling the ultimate of final goal of the system. Local representations of cognitive data are those, which help the system to surmount local problems. Associated with these are two cognitive maps retentive terms called relatively long-term and relatively short-term memories.
Cognitive map based foraging is reported in most ant species. The effective utilization of these maps in devising foraging patterns and strategies enables the ant colony to successfully raid a patch of terrain for objects of interest. Cognitive memory is the ability of the ants to remember points of interest on the terrain, which may be useful for them in foraging activities globally. The utilization of cognitive memory in foraging and navigation effectively enhances the maximization of resources in the foraging process. In this paper we deal with the implementation of a foraging strategy for the ants to bring an increase in the overall efficiency of the mine detection process.

Ants, to effectively carry out their colony level foraging, use cognitive meandering or moving among cognitive maps in a controlled fashion. The amount of adaptivity that is directly related to the computational and memory management resources that the ants are equipped with. Cognitive meandering in ants is the ability used in foraging wherein local foraging decisions are made based on the history of visits to the terrain. Thus newer regions are constantly explored in the proximity of the nest. Random fluctuations in exploration routes are helpful in overcoming deadlocks and cyclic paths in foraging.

4 The Mine Detection Problem

The mine detection problem involves the detection and the demining of randomly placed mines over a field by a finite number of agents with resource constraints [1, 6, 13]. The agents in our case are the ants carrying out their foraging task. The mines were uniformly distributed over a field in our simulations. The demining of any mine involves the collective actions of a certain number of ants, four in our simulations. The main goal of the work is to eliminate the central intelligence in driving the act for the completion of the task. We have applied a swarm intelligence based technique to the problem. This need for a collective action of a certain number of ants for demining brings the recruitment mechanism into the picture.

When an ant reaches a mine it spreads a scent around the mine in resemblance to short range recruitment (SRR) found in certain ant colonies [2, 8, 9, 10]. This scent decreases exponentially in a region around it as shown in Figure 1. The formulation for the scent decay in our simulations is shown in equation 1. The spread of the scent is equivalent to physical stigmergy, which are basically physical changes produced in the environment so as to bring about a desired reaction, in this case attraction of other ants around the mine to the mine. The ants around the mine follow the scent’s increasing gradient and finally land themselves around the mine.

\[ S(x, y) = Ae^{-\alpha(Min(|x-x_i|,|y-y_j|))} \]  

Figure 1. Scent distribution around a mine.

4.1 The Foraging Strategy

The foraging strategy for the ants involved in the mine detection task is based on cognitive meandering over the field [3, 5, 14]. In this strategy the ants map the foraging terrain, into regions called cognitive regions. The ants are initially assumed to start from the boundary of the minefield for practical reasons. During foraging, the ants meander from one cognitive sub region to another. The ants have the ability to locate themselves at any point within the minefield with respect to certain references. The reference in our case is the boundary of the minefield. Figure 2 shows an ant moving in the realm of the cognitive regions from point A to point B.

Figure 2. Cognitive map based ant foraging

At point B the ant has to decide on which cognitive region to chose from its neighboring cognitive regions. This decision is made based on the knowledge of the mines it has demined in its adjoining regions. The ant in cognitive region C or to cognitive region D based on the fact that either C or D has the highest probability of detecting mines in them. Another fact on which this decision can be made is the history of visits it has made to cognitive regions C or.
D. If two or more cognitive regions are equally weighed in terms of the ant's knowledge then a random decision is made between the equally weighed cognitive regions. In our simulations, we have modeled the local decision of the ants in picking the foraging cognitive region based on the demined/undemined mine knowledge of its adjoining cognitive regions. The probability distribution function used in the model is given is equation 2. The term $\beta$ in the equation is a measure to show the relative importance of the demined and undemined mine knowledge of the ants.

$$P(\text{cognitive \_ region}_k) = \frac{1}{(1 + \beta)} \left( \frac{N - b_k}{(n - 1)N} + \frac{\beta a_k}{M} \right)$$  \hspace{1cm} (2)$$

In equation 2, $N$ and $M$ represent the total knowledge of the mined and demined mines in the adjoining cognitive regions of the ant's present cognitive region. Terms $a_k$ and $b_k$ represent the undemined and demined information of cognitive \_ region$_k$ adjoining the ant's present cognitive region. The fact equation 2 sums up to one over the entire ant's adjoining cognitive regions assure that it is a valid probability density function.

4.2 The Demining Process

The process of demining of a single mine $M$ requires the collective action of four ants ($A, B, C, D$) in our simulations as shown in Figure 3. This makes the phenomenon of partner recruitment essential in the process. Partner recruitment techniques involve the spreading of a spatial scent around the mine. The scent spread has the property that its strength attenuates over distance from the mine. This property facilitates the ants to follow the scent and eventually detect the mine. When the ants detect a mine it goes into a waiting mode for allowing other to follow up to the mine location.

![Figure 3. Actions of four ants in demining a single mine](image)

The entire process of mine detection is modeled as three distinct behaviors, foraging, trail following, and waiting as shown in Figure 4. The shift from the foraging state to the trail following state is initiated when an ant detects a scent during its process of foraging. The ants do not lose the ability to forage for mine in the scent following behavior. This helps in reducing false alarms.

4.3 Freezing

An important and interesting factor to be noted in this model for mine detection is a factor called freezing [9, 10]. Freezing is defined as a situation that arises when behavioral expectation becomes mutual or cyclic and the whole system goes into a deadlock. In our simulations freezing could occur when all of the ants go into the waiting mode and expect others to follow it. Normally this can occur when the ratio of the number of mines to be detected to that of the ants employed for detection is large.

Freezing could be avoided by employing a threshold time for the waiting behavior. This is achieved by allowing the ants in the waiting state to resume their foraging action after a finite amount of time. This time is called the threshold time for waiting. The threshold time for waiting can be prefixed to be a constant quantity or can be allowed to vary depending on the number of ants present at the mine site or the position of the mine over the minefield. An important point to be noted in such a scenario is the fact that the ants could be attracted to the mine they are trying to get away from. To overcome this problem we model only those ants to be able to spread the scent which has a behavioral transition from foraging to trail following. Thus at a given point of time there can be instances where a mine detected by ants do not have the scent spread around it. The inculcation of the freezing avoiding process in the model has a detrimental effect to the performance of the ants but it helps in eliminating the unwanted freezing state from occurring and assures total convergence.

5 Analysis and Results

Our simulations were carried out on a rectangular minefield, with mines uniformly distributed. Given below in Figure 5 is a plot of the number of iterations took for runs performed on various combinations of ants and mines over a field of 100x100. The iteration counts more than 3000 were ignored. These are regions where freezing could be prominently seen. The field size 100x100 was chosen because it was easy enough for us to obtain symmetrical cognitive regions and sub-regions from the main field.
we conducted simulation runs on a smaller field size of 50x50 to verify the same trends that we obtained in the 100x100 field. A compilation of the results obtained from the 50x50 field is done in Figure 5. Results seen in Figure 5 and Figure 6 show that the iteration time increases with the mine-to-ant ratio. These results were obtained for a waiting threshold time of 50 iterations. Ants with cognitive maps for foraging showed dramatic performance increase as compared to random foraging ants. The comparison chart shown in Figure 6 approves this performance increase.

Figure 7 shows the adaptivity that the ants equipped with cognitive maps show as compared to randomly foraging ants. It is evident from Figure 7 that the rate at which the mines are defused progressively increases in the case of ants employed with cognitive maps whereas it decreases or is stagnant in the case of those without cognitive maps. Decrease in the rate of mine detection as time progresses reflects randomness and increase in the rate shows adaptation. Thus adaptivity is clearly seen in ants employed with memory. The concept of cognitive meandering brought into the foraging strategy of the ants has enhanced the adaptivity rate and thus an increase in performance is seen.

6 Design of Swarm Robots

The design of Groundscout robots for the demonstration of the Mine Detection algorithm is in process at the Multi agent Bio-Robotics Lab, Rochester Institute of Technology. Various sensory and communication resources present on the groundsouts are used for the design. The ants are equipped with cognitive map realizations of their foraging terrain. The performance will be scrutinized against factors like false alarms caused by the robots, memory loss of robots involved in the mine detection process, and obstacle avoidance. A Phillips microcontroller is used for the design of the mine detection algorithms. Sensors like ultrasonic sensors, infrared sensors and proximity sensors would be some of the resources available for the design. The robustness and the practicality of the algorithm will be verified in this experiment. Figure 8 shows the current version of the micro-robot to be used.
7 Conclusions

Even today the techniques employed for the detection of mines are traditional and outdated. Robots could be conceived as an alternative to these traditional techniques, which primarily employ humans for the task [3, 5, 10, 14]. The involvement of robots for mine detection requires a robust model for foraging and demining. Models based on ant colonies are simple and non-communicating makes it highly preferred for robot design. This requires building a confidence that robots could be used for the task successfully. We have attempted to develop this confidence not only at the simulation level but also have realized the robots practically and thus carrying the confidence levels to practical levels. Our simulation results show that in almost all cases the convergence is well assured.

8 Future Work

There are certain areas where the present work could be improved on. The time required for completing the detection of the mines in the region, can be further reduced if the ants use the information of the mines that it has detected in deciding on the future foraging strategy more effectively. This can be achieved by giving a foraging strategy which uses both pheromone and cognitive map based foraging. A cost function approach can also be utilized for such a set up. By updated mine distribution we mean the distribution that an ant would have after it has defused a mine at a particular point, in comparison to the initial mine distribution that it had assumed. Analysis of the threshold time factor applied to the waiting behavior can enhance the performance of the algorithm. Also the algorithm could be applied to scenarios where the mines can be mobile. Simulations can be performed in situations where the nature of the mines can be different and demand a defusing technique different from the rest of the mines. The swarm robot design will be carried out to verify the performance of the algorithm on a practical basis.

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References


