Neurocomputing 148 (2015) 83–90

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Superadditive effect of multi-robot coordination in the exploration of unknown environments via stigmergy

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ARTICLE INFO

Article history:
Received 2 April 2012
Received in revised form
27 June 2012
Accepted 31 July 2012
Available online 1 August 2014

Keywords:
Stigmergy
Pheromones
Swarm robotics
Exploration
Multi-robot coordination

ABSTRACT

We propose a simple yet efficient way of coordinating multiple homogeneous robots in the exploration of unknown environments. A guided probabilistic exploration of an unknown environment is achieved via combining random movement with pheromone-based stigmergic guidance. The emergent strategy is shown to provide a scalable solution to multi-robot coordination for the area exploration task, with a faster than linear speed-up with the addition of new robots. We utilize an approach to evaluating the desired exploration behavior that emphasizes "surveying" rather than "scanning" the environment. We analyze the emergent exploration strategies and demonstrate their effectiveness in higher complexity environments.

1. Introduction

Pheromones provide a stigmergic medium of communication, which influence the future actions of a single or a group of individuals via changes made to the environment. In biology, pheromones serve a number of functions for living organisms, including aggregation, attraction, alarm propagation, territorial marking and group decision making [22]. Stigmergy allows the history of an individual's actions to be tracked without the need to construct a model of the environment within the individuals own memory; making the emergence of higher complexity behaviors from a group of simple individuals possible.

By using the actual physical environment, the communication in a multi-robot system can be easily expanded to more than just a few robots. The utilization of the physical environment provides the ability to store information without any inter-robot communication overhead, and without any worries about limitations on communication ranges [19] or limitations on the scalability of the system due to communication overhead [10]. Thus, intelligent groups can arise from extremely simple individuals. The use of stigmergic pheromone-based communications in robotics has a range of other potential advantages, such as the possible ability to adjust the range and persistence of a pheromone, not being limited to line-of-sight, the ability of pheromones to propagate through environment (while forming gradients), and freeing the individual robots from the burden of communication management and processing—usually involved with other forms of commonly used communications (such as radio, IR, visual, and audio). Utilizing a real stigmergic communication would be an efficient method of achieving such emergent behavior with low overhead.

In this work we present a simple algorithm for the coordination of multiple robots to achieve emergent exploration of an unknown environment. The algorithm presented utilizes stigmergic markers for inter-robot communication, which allows the implementation of the algorithm on simple robots, yet achieve complex organized behavior. The algorithm presented introduces random movements via wall avoidance as well as a bias towards continuous forward movement in order to achieve quicker exploration than the previously suggested stigmergy-based multi-robot exploration algorithms. The emergent strategy will be shown to achieve a "divide-and-conquer" approach for the exploration task which proves to be a better strategy than a greedy exploration. We consider emergence as a phenomenon of local interactions creating global properties [7]. Thus, the resultant behavior of a group of robots in the exploration of an environment is the emergent behavior.

In our work, we assume complete freedom on the properties of the pheromones available and focus on providing an optimal and simple system for efficient exploration. Most of the previously reported simulation experiments in the exploration of unknown spaces make some unrealistic assumptions in order to simplify the simulation environment; such as the ability of the individual robots to execute perfect discreet movements of fixed distances and the ability to divide a given environment into a grid to allow discreet movement of robots. It is common to provide such simplifications in the physics and movement of robots in the simula-

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http://dx.doi.org/10.1016/j.neucom.2012.07.062
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tions utilized for investigating the exploration algorithms [4,6,8]. The problems of making such assumptions in simulation phase would emerge if the algorithm was to be implemented in real robots. Furthermore, when realistic simulators or real robots are used for testing the capabilities of an algorithm in exploring an unknown area, the maps used are considerably simpler: often relatively small maps with no obstacles are used in these type of experiments [12,20]. We believe that one of the reasons for exploration to be a difficult task with real robots or realistic simulators is because of the way exploration is defined. The common practice used for evaluating the success of a system in exploration is to consider the time it takes to cover all the points in a given map. Such an approach to exploration of an area would be useful for applications such as mine sweeping, surface inspection and cleaning, where it is crucial to visit all the locations in the given area. On the other hand for tasks such as search and rescue, there is no need to visit every available location on the map, but only to visit some key locations that can get all the remaining locations on the map within the sensory range of the robots.

The work presented here aims to demonstrate the use of pheromone-based communication in achieving quick and efficient exploration of unknown environments via realistically simulated robots. We utilize a simulation environment (Webots) that closely models the physics of two wheeled differentially steered mobile robots and their interactions with the environment. We define “exploration” as the ability to visit the key locations in a map that provide enough information about the boundaries of the explored areas and a visibility of all the area within those boundaries. We design an algorithm that is similar to the “node counting” algorithm described in [20], however, in our case the goal is to achieve a quick “survey” of an area by visiting key locations as quickly as possible. Section 2 provides a brief summary of the related work in stigmergic communication in swarm robotics. In Section 3, we describe our pheromone-based algorithm. In Section 4, we evaluate the performance of the algorithm and analyze the emerged exploration strategies. Section 5 provides a discussion on the results achieved. Finally, we conclude our work and provide some direction for future work in Section 6.

2. Related work

Biological pheromones have already been an inspiration to many successful swarm control algorithms aimed at real robots. Robots that utilize stigmergic trails to communicate with each other have been shown to effectively coordinate and quickly explore a given terrain [1,20]. However, a common approach is to replace physical stigmergy with wireless signals that involve direct robot to robot or robot to communication-point messaging. Simulated pheromones have been used to coordinate groups of robots for various tasks. Payton et al. utilize infra-red communication among robots to create pheromone-like gradients via nearest neighbor communication from one point to another [12]. Sauter et al. use virtual pheromones, simulated within the memory of each robot in a heterogeneous robotic system to control and coordinate the actions of the robots in surveillance and base protection missions [17]: in this case the pheromone map is built and maintained as a result of inter-robot communications, GPS, and a video camera system. A similar approach to the latter was also used for path planning in [11]. The aforementioned methods have been demonstrated to work well in the domains they were applied in, however they come with limitations related to communications, memory requirements, fault tolerance, and scalability of the overall system. Indeed the aforementioned works do not try to solve the inherent problems that exist in wireless communication via stigmergy, but use stigmergic communication as an inspiration for multi-robot coordination. There are various works that achieve highly sophisticated multi-robot coordination without the need to model stigmergy, e.g. [2,3,10]. Our goal is to provide an algorithm based on the use of real stigmergic markers for achieving exploration with minimal computational and communication complexity.

The use of physical substances for pheromone-based communication within robots is problematic and poorly understood. However, there is undergoing work in improving their use with promising results, and it is predicted that with improvements in sensing technology it may be possible that a robot could carry a lifetime supply of chemicals [15]. There are various approaches that can be taken in utilizing real stigmergic communication among robots [6,14,16,20], each with their own advantages and disadvantages, but all with the common aim of exploiting the environment as a resource of communication in achieving complex behaviors from a group of simple robots. Beckers et al. successfully built a group of mobile robots that operate with a very simple algorithm and work collectively to achieve a foraging behavior by using the objects gathered as sources of stigmergic information [1]. Russell developed short-lived navigational markers for small robots where heat trails were used to replace pheromone trails [16]. Svennebring and Koenig studied terrain-covering robots that used a black marker to form trails on the floor [20]. Ferranti et al. demonstrated the use of the exploration of unknown environments via agents that make use of “tags” (such as motes or RFIDs) as stigmergic markers [6]. Purnamadjaja and Russel showed that aggregation with real robots using real chemicals is possible [14], who also later on use real chemicals to establish two way communication between robots [15].

3. Pheromone-based stigmergic coordination

As in biology, our model uses the environment as a medium of communication by leaving traces of pheromones. These pheromones are deposited by the robots and are also detected by them when they are within the proximity of the pheromone. The pheromone-based control provides an indirect (stigmergic) communication mechanism among a group of homogeneous robots. This provides a simple means of decentralized coordination of multiple-robots, giving rise to a fault tolerant system. We implement a reactive, three-layered subsumption architecture for the controllers of the robots, where each layer implements one basic behavior: random walk (“exploration”) is the behavior corresponding to the lowest priority layer, while the pheromone-based coordination (“exploitation”) is the middle layer, and the wall avoiding behavior is realized by the highest priority architectural level.

The algorithm used for the pheromone-based control is similar to the “node counting without cleaning” in [20], and it is detailed in Algorithm 1. Key differences in the algorithms include the ability of the algorithm presented here to use variable concentrations in depositing pheromones, ignoring pheromones below a certain concentration, evaporation and diffusion of pheromones, and a bias towards forward movement. In our case we have a bias towards making smaller turns when there are same levels of pheromone concentrations in more than one direction. In our approach, the pheromone-related perceptions of the robots comprise the concentration of the pheromone in five directions only (NORTH, NORTH EAST, NORTH WEST, EAST, and WEST; NORTH being the face forward direction), instead of all eight directions in order to further encourage forward movement.

Algorithm 1. The pheromone-based robot control.

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$LPC$ = Lowest pheromone concentration
$NPC$ = Pheromone concentration in front of the robot
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