Pheromone-guided Dispersion for Swarms of Robots

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Abstract

We propose and analyze an algorithm for dispersing a swarm of robots in an unknown environment R. We use simple robots with the ability to leave a pheromone behind. Robots can get local information with their sensors but cannot communicate with other robots. The primary objective is to minimize the *makespan*, that is, the time to *fill* the entire region. We achieve a competitive ratio of $O(\log(k+1))$ where k is the number of doorways.

1 Introduction

Multiagent robotics has been an active field in the recent years and there has been many works on distributed control and coordination of a set of autonomous robots. Principe et al. [6, 16] and Suzuki et al. [5, 19, 20] have studied pattern formation in distributed autonomous robotics under various models of robots with minimal capabilities. The related flocking problem, which requires that a set of robots follow a leader while maintaining a formation, has been studied in several recent papers; see, e.g., [1, 2, 10] Wagner et al. [3, 21, 22, 23] developed multi-robot algorithms, inspired by ant behaviors, for searching and covering. Payton et al. [15, 14] propose the notion of "pheromone robotics" for world-embedded computation.

A natural problem that arises in the study of "swarm robotics" is how to obtain a quick dispersal and filling of the environment while maintaining the connectivity of the robot swarm. That is, devise algorithms to reposition robot swarms in an uknown domain such that every point of the domain is seen by some robots and for any given pair of robots we can establish a visibility chain in which consecutive robots can see each other.

Motivations for this behavior can be found on a diverse spectrum of applications for different domains: space exploration, medicine, military, and industry, just to name a few. Common applications include exploration and map extraction of an unknown domain, mine sweeping, and guarding.

A big proportion of previously developed dispersion algorithms rely on greedy strategies such as *go-for-free space* [13], where robots move to fill unoccupied space; *artificial physics* [18] strategies, where neighboring robots exert "forces" on each other: repulsion forces if the robots are closer than the target separation, and attraction forces if the neighboring robots are farther away (and the swarm is in danger of becoming disconnected); and *potential fields* [11, 17]. Almost all of them require communication, albeit local, within pairs of robots

Our goal is to develop dispersion algorithm on discrete environments. A discrete environment is composed of *squares* or *pixels* that form a connected subset of the integer grid. There is at most one robot per pixel and robots move horizontally or vertically at unit speed. Robots enter domain R through $k \geq 1$ *door pixels*, each of which acts as an infinite source of robots.

Our robots can be implemented with $O(1)$-size memory and $O(1)$-size sensor range. There is no direct communication between robots, instead, they leave pheromones as traces for others to follow. The robots are decentralized and move only according to local information.

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2 Pheromone-guided Dispersion

As the robots move through the domain, they leave a pheromone trail behind. At each step a robot surveys its local neighborhood (Figure 1) and decides its next move according to the positioning of the pheromones, other robots, and obstacles. This process does not require direct communication between robots. For the case of multiple doors, the pheromones are differentiated by *teams* corresponding to each particular doorway.

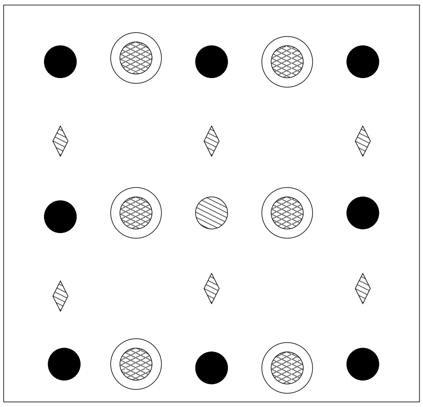

Figure 1: Local information available to a robot (at the center in gray) at a particular step of the simulation. Diamonds represent pheromones, double circled points represent stopped robots, and black points are currently moving robots

The main goal for a robot is to find a spot in the domain where it can *stop*, preferrably at the shortest possible amount of traveled distance. This stopping spot can only be found at the left or the right of the direction the robot is moving, so not to interrupt the flow of its line. To keep the robots advancing through the domain and to avoid blocking paths, a spot is available for stopping only if its surrounding spots do not hold a stopped robot. (Figure 2)

If a robot does not have spot available to stop it should try to keep moving following these set of priority rules:

- Follow the path is was moving on. Otherwise...
- Try to make a turn that does not conflict with other teams of robots. Otherwise...
- Wait for a constant number of iterations. If there is no possibility of continuing it should stop.

The pheromones that robot utilize to make trails contain only the *team-tag* information. Each pheromone has a constant size lifetime after which it *dissapears*. Since each moving robot has another robot following behind at a close distance pheromones get replaced by newer ones as the trail keeps moving.

Summary of Results With a simpler heuristic and a lack of communication our algorithm obtained similar results as those expressed by Hsiang et al [12]. We prove that our algorithms have optimal competitive ratio of $O(\log(k+1))$ where k is the number of doorways. By having the robots searching for the closest stopping place we ensure a more efficient use of individual resources (power supply), while achieving a complete stop for the run with no need of general communication.

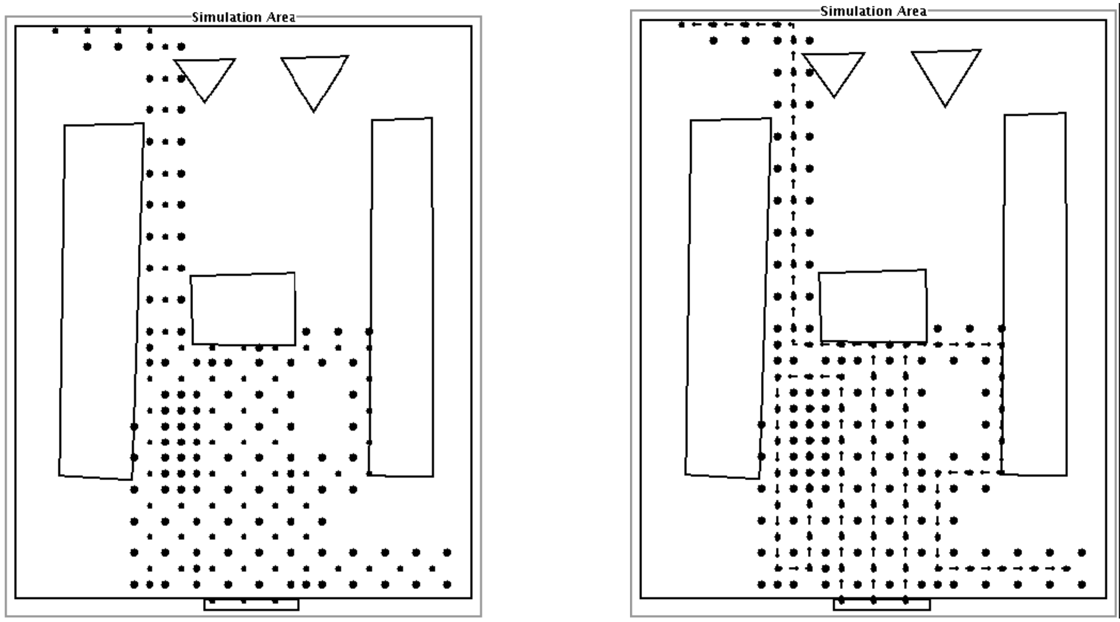

Figure 2: The figure on the left illustrates an instance of the simulation. Robots are entering the domain through the door located at the bottom center of the figure. The figure on the right expands the original at the left with the display of the pheromones that guide the robots.

3 Future Work

- We modified our heuristic, requiring for a robot to stop only when it does not have any other place to move to.
- We are implementing a new strategy that involves *random branching*, in which teams coming from the same doorway, split and branch randomly along the march.
- Similar heuristics are being implemented for continuous environments. For those environments the step size, and the steering angle of a robot are subject to measurement errors.

References

[1] T. Balch and R. C. Arkin. Behavior-based formation control for multi-robot teams. *IEEE Transactions on Robotics and Automation*, 14(6):926–939, 1998.

[2] O. B. Bayazit, J.-M. Lien, and N. M. Amato. Better flocking behaviors using rule-based roadmaps. In *Proc. Fifth International Workshop on Algorithmic Foundations of Robotics*, 2002.

[3] A. M. Bruckstein, C. L. Mallows, and I. A. Wagner. Probabilistic pursuits on the grid. *American Mathematical Monthly*, 104(4):323–343, 1997.

[4] X. Deng, T. Kameda, and C. Papadimitriou. How to learn an unknown environment I: The rectilinear case. *Journal of the ACM*, 45(2):215–245, Mar. 1998.

[5] A. Dumitrescu, I. Suzuki, and M. Yamashita. High speed formations of reconfigurable modular robotic systems. In *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA '02)*, pages 123–128, 2002.

[6] P. Flocchini, G. Prencipe, N. Santoro, and P. Widmayer. Distributed coordination of a set of autonomous mobile robots. In *Proc. IEEE Intelligent Vehicle Symposium (IV 2000)*, pages 480–485, 2000.

[7] D. Gage. Many-robot systems. http://www.spawar.navy.mil/robots/research/manyrobo/manyrobo.html.

[8] D. Gage. Sensor abstractions to support many-robot systems. In *Proceedings of SPIE Mobile Robots VII, Boston MA, 18-20 November 1992, Volume 1831*, pages 235–246, 1992.

[9] D. Gage. An evolutionary strategy for achieving autonomous navigation. In *SPIE Proc. 3525: Mobile Robots XIII, Boston MA, November*, 1998.

[10] V. Gervasi and G. Prencipe. Flocking by a set of autonomous mobile robots. Technical Report TR-01-24, University of Pisa, Dipartimento di Informatica, Oct. 2001.

[11] A. Howard, M. J. Mataric, and G. S. Sukhatme. Mobile sensor network deployment using potential fields: A distributed scalable solution to the area coverage problem. In H. Asama, T. Arai, T. Fukuda, and T. Hasegawa, editors, *Proc. 6th International Symposium on Distributed Autonomous Robotic Systems*, page to appear, Fukuoka, Japan, 2002. Springer-Verlag.

[12] T.-R. Hsiang, E. M. Arkin, M. Bender, S. P. Fekete, and J. S. B. Mitchell. Algorithms for rapidly dispersing robot swarms in unknown environments. *Fifth International Workshop on Algorithmic Foundations of Robotics*, December 15-17 2002.

[13] N. Jovanovic, T.-R. Hsiang, and M. Sztainberg. Experimental comparison of dispersion protocols for robot swarms. Technical report, Stony Brook University, 2002.

[14] D. Payton, M. Daily, R. Estkowski, M. Howard, and C. Lee. Pheromone robotics. *Autonomous Robots*, pages 319–324, 2001.

[15] D. Payton, R. Estkowski, and M. Howard. Progress in pheromone robotics. *Proc. 7th International Conference on Intelligent Autonomous Systems*, 2002.

[16] G. Prencipe. *Distributed Coordination of a Set of Autonomous Mobile Robots.* PhD thesis, Dipartimento di Informatica, Università degli Studi di Pisa, 2002.

[17] J. H. Reif and H. Wang. Social potential fields: A distributed behavioral control for autonomous robots. *Robotics and Autonomous Systems*, 27(3):171–194, 1999.

[18] W. Spears and D. Gordon. Using artificial physics to control agents. In *In IEEE International Conference on Information, Intelligence, and Systems.*, 1999.

[19] K. Sugihara and I. Suzuki. Distributed algorithms for formation of geometric patterns with many mobile robots. *Journal of Robotic Systems 13, 3*, pages 127–139, 1996.

[20] I. Suzuki and M. Yamashita. Distributed anonymous mobile robots: Formation of geometric patterns. *SIAM Journal on Computing*, 28(4):1347–1363, 1999.

[21] I. Wagner and A. Bruckstein. Cooperative cleaners: a study in ant robotics. Technical Report CIS9512, Technion, 1995.

[22] I. Wagner, M. Lindenbaum, and A. Bruckstein. Distributed covering by ant-robots using evaporating traces. *IEEE Transactions on Robotics and Automation*, 15(5):918–933, 1999.

[23] I. A. Wagner, M. Lindenbaum, and A. M. Bruckstein. Efficiently searching a graph by a smell-oriented vertex process. *Annals of Mathematics and Artificial Intelligence*, 24(1-4):211–223, 1998.

[24] I. A. Wagner, M. Lindenbaum, and A. M. Bruckstein. Mac vs. pc - determinism and randomness as complementary approaches to robotic exploration of continuous unknown domains. Technical Report CIS9814, Technion, 1998.