Distributed Pattern Formation by Autonomous Robot Swarm

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ABSTRACT

Arbitrary Pattern Formation is a fundamental robot coordination problem. The problem asks for a distributed algorithm that allows a swarm of autonomous mobile robots to form any pattern given as input. The majority of the works in the literature investigate the problem under models with very idealistic assumptions regarding motion and sensing capabilities of the robots. We investigate the problem, aiming towards removing these assumptions and understanding their effect on the solvability of the problem.

CCS CONCEPTS

• **Theory of computation → Self-organization**.

KEYWORDS

Robot Swarm, Pattern Formation, Distributed Algorithm

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1 INTRODUCTION

A robot swarm is a system of relatively simple autonomous mobile robots that collaboratively execute some complex tasks. Robot swarms take inspiration from collective behaviors of biological systems such as ant colonies, swarm of bees, schooling of fish, flocking of birds etc. Although the individual entities in such biological swarms have limited capabilities, they exhibit complex behaviors as a group and can collectively execute difficult tasks. The aim of swarm robotics is to likewise have a system of a large number of relatively simple generic robots to collectively execute complex tasks through the use of local rules without any centralized control. This approach offers several advantages over traditional single robots such as low cost and high stability, robustness, scalability and flexibility. Owing to its potential applications in a wide range of practical problems, distributed coordination of robot swarms has attracted considerable research interest in the last two decades.

2 MODEL AND PROBLEM

In the traditional framework of theoretical studies, a robot swarm is modeled as a team of autonomous, anonymous and identical computational entities that can move in the plane. The robots do not have access to any global coordinate system. Each robot is equipped with sensor capabilities that enable it to perceive the positions of other robots. The robots operate in Look-Compute-Move (LCM) cycles. In each cycle, a robot takes a snapshot of the positions of the other robots (Look); based on this snapshot, it executes a deterministic algorithm to determine a destination (Compute); and it moves towards the computed destination (Move). Based on the activation and timing of the robots, there are three types of schedulers considered in the literature. In the fully synchronous setting (FSync), the robots operate in synchronous rounds. All the robots are activated in each round, where they take their snapshots at the same time, and then execute their moves simultaneously. The semi-synchronous model (SSync) is same as the FSync model, except for the fact that not all robots are necessarily activated in each round. The most general model is the asynchronous model (ASync) where there are no assumptions regarding the synchronization and duration of the actions of the robots. The robots usually have either no memory (*oblivious* robots) or very little memory available to remember past observations and calculations. Also, they either have no means of direct communication (*silent* robots) or have some very weak communication mechanism (e.g., an externally visible light that can assume a small number of predefined colors).

We study the Arbitrary Pattern Formation problem [5–13], which is a fundamental robot coordination problem and one of the most studied problems in this field. The problem asks for a distributed algorithm that allows the robots in the swarm to reposition themselves to form any pattern given as input. However, the majority of the works investigate the problem under models with very idealistic assumptions, e.g., accurate movements, unlimited

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sensing capabilities, error-free measurements etc. We investigate the problem, aiming towards removing these assumptions and understanding their effect on the solvability of the problem.

3 OUR RESULTS

In [2], we study the Arbitrary Pattern Formation problem on a two dimensional infinite grid. In the standard continuous setting, the robots can move in any direction and by any amount. Certain models also permit the robots to move along curved trajectories, in particular, circumference of a circle. The correctness of the algorithms rely on the accurate execution of the movements. However, for robots with weak mechanical capabilities, it may not be possible to execute such intricate movements with precision. This motivates us to consider the problem in a grid based terrain where the movements of the robots are restricted only along grid lines and only to a neighboring grid point in each step. Grid type floor layouts can be easily implemented in real life robot navigation systems using magnets or optical guidances. From an algorithmic perspective, the restrictions imposed by the model on the movements make it challenging to devise a collisionless movement strategy. In this setting, we show the Arbitrary Pattern Formation is solvable by a set of oblivious, silent and asynchronous robots from any asymmetric initial configuration.

There can be two criticisms towards the grid model. First, from a theoretical perspective, the grid structure of the terrain provides a partial agreement among the local coordinate systems of the robots. In this sense, the grid model is stronger than the continuous plane model with no agreement on coordinate system. Secondly, from a practical perspective, there can be application scenarios where such grid type floor layouts are not available or can not be set up. Therefore in [3], we consider the usual continuous setting, but assuming that the movements of the robots may be inaccurate. The movement model assumes errors in both direction and extent of the intended movement. We show that the exact version of the Arbitrary Pattern Formation problem is unsolvable in this model. So we consider a relaxed version of the problem called the Approximate Arbitrary Pattern Formation problem. With no agreement on coordinate system, the problem is unsolvable if the initial configuration has rotational symmetry with no robot at the centre of rotation or reflectional symmetry with no robot on the reflection axis. From all other initial configurations, we solve the problem by a team of 1) oblivious, silent and semi-synchronous robots and 2) oblivious and asynchronous robots that can communicate with each other with (only externally) visible lights.

The majority of the literature that studies the Arbitrary Pattern Formation problem consider robots with full visibility. However, if the robots are equipped with camera sensors, then it is unrealistic to assume that each robot can observe all other robots in the swarm, as the line of sight of a robot can be obstructed by the presence of other robots. So we next study the problem in the obstructed visibility or opaque robot model. In [4], we consider opaque point robots where the robots are modeled as points on the plane and it is assumed that a robot is able to see another robot if and only if no other robot lies on the line segment joining them. We show that the problem is unsolvable by oblivious and silent robots. So we consider robots equipped with (both internally and externally) visible lights. The lights serve both as a weak explicit communication mechanism and a form of internal memory. In this model, we have shown that Arbitrary Pattern Formation can be solved from any initial configuration in the two axis agreement setting (i.e., the local coordinate systems of the robots agree on the direction and orientation of both coordinate axes). In the one axis agreement setting (i.e., the local coordinate systems of the robots agree on the direction and orientation of only one coordinate axis), the problem is solvable if and only if the initial configuration does not have reflectional symmetry with respect to a line which is parallel to the agreed axis with no robots lying on it. Then in [1], we extend these results to the more realistic opaque fat robot model where the robots are modeled as identical opaque disks.

REFERENCES

[1] Kaustav Bose, Ranendu Adhikary, Manash Kumar Kundu, and Buddhadeb Sau. 2020. Arbitrary Pattern Formation by Opaque Fat Robots with Lights. In *Algorithms and Discrete Applied Mathematics - 6th International Conference, CALDAM 2020, Hyderabad, India, February 13-15, 2020, Proceedings (Lecture Notes in Computer Science, Vol. 12016)*, Manoj Changat and Sandip Das (Eds.). Springer, 347–359. https://doi.org/10.1007/978-3-030-39219-2_28

[2] Kaustav Bose, Ranendu Adhikary, Manash Kumar Kundu, and Buddhadeb Sau. 2020. Arbitrary pattern formation on infinite grid by asynchronous oblivious robots. *Theor. Comput. Sci.* 815 (2020), 213–227. https://doi.org/10.1016/j.tcs.2020.02.016

[3] Kaustav Bose, Archak Das, and Buddhadeb Sau. 2020. Pattern Formation by Robots with Inaccurate Movements. *CoRR* abs/2010.09667 (2020). arXiv:2010.09667 https://arxiv.org/abs/2010.09667

[4] Kaustav Bose, Manash Kumar Kundu, Ranendu Adhikary, and Buddhadeb Sau. 2021. Arbitrary pattern formation by asynchronous opaque robots with lights. *Theor. Comput. Sci.* 849 (2021), 138–158. https://doi.org/10.1016/j.tcs.2020.10.015

[5] Quentin Bramas and Sébastien Tixeuil. 2016. Brief Announcement: Probabilistic Asynchronous Arbitrary Pattern Formation. In *Proc. of the 2016 ACM Symposium on Principles of Distributed Computing, PODC 2016, Chicago, IL, USA*. 443–445. https://doi.org/10.1145/2933057.2933074

[6] Serafino Cicerone, Gabriele Di Stefano, and Alfredo Navarra. 2019. Asynchronous Arbitrary Pattern Formation: the effects of a rigorous approach. *Distributed Comput.* 32, 2 (2019), 91–132. https://doi.org/10.1007/s00446-018-0325-7

[7] Yoann Dieudonné, Franck Petit, and Vincent Villain. 2010. Leader Election Problem versus Pattern Formation Problem. In *Proc. of 24th International Symposium on Distributed Computing, DISC 2010, Cambridge, MA, USA*. 267–281. https://doi.org/10.1007/978-3-642-15763-9_26

[8] Paola Flocchini, Giuseppe Prencipe, Nicola Santoro, and Peter Widmayer. 2008. Arbitrary pattern formation by asynchronous, anonymous, oblivious robots. *Theor. Comput. Sci.* 407, 1-3 (2008), 412–447. https://doi.org/10.1016/j.tcs.2008.07.026

[9] Nao Fujinaga, Yukiko Yamauchi, Hirotaka Ono, Shuji Kijima, and Masafumi Yamashita. 2015. Pattern Formation by Oblivious Asynchronous Mobile Robots. *SIAM J. Comput.* 44, 3 (2015), 740–785. https://doi.org/10.1137/140958682

[10] Ichiro Suzuki and Masafumi Yamashita. 1999. Distributed Anonymous Mobile Robots: Formation of Geometric Patterns. *SIAM J. Comput.* 28, 4 (1999), 1347–1363. https://doi.org/10.1137/S009753979628292X

[11] Ramachandran Vaidyanathan, Gokarna Sharma, and Jerry L. Trahan. 2018. On Fast Pattern Formation by Autonomous Robots. In *Proc. of 20th International Symposium on Stabilization, Safety, and Security of Distributed Systems, SSS 2018, Tokyo, Japan*. 203–220. https://doi.org/10.1007/978-3-030-03232-6_14

[12] Masafumi Yamashita and Ichiro Suzuki. 2010. Characterizing geometric patterns formable by oblivious anonymous mobile robots. *Theor. Comput. Sci.* 411, 26-28 (2010), 2433–2453. https://doi.org/10.1016/j.tcs.2010.01.037

[13] Yukiko Yamauchi and Masafumi Yamashita. 2014. Randomized Pattern Formation Algorithm for Asynchronous Oblivious Mobile Robots. In *Proc. of 28th International Symposium on Distributed Computing, DISC 2014, Austin, TX, USA*. 137–151. https://doi.org/10.1007/978-3-662-45174-8_10