Brief Announcement: Asynchronous Filling by Myopic Luminous Robots*

Attila Hideg[1] and Tamás Lukovszki[2]

[1] Department of Automation and Applied Informatics,
Budapest University of Technology and Economics, Budapest, Hungary
`Attila.Hideg@aut.bme.hu`

[2] Faculty of Informatics, Eötvös Loránd University, Budapest, Hungary
`lukovszki@inf.elte.hu`

Abstract. We consider the problem of filling an unknown area represented by an arbitrary connected graph of n vertices by mobile luminous robots. In this problem, the robots enter the graph one-by-one through a specific vertex, called the Door, and they eventually have to cover all vertices of the graph while avoiding collisions. The robots are anonymous and make decisions driven by the same local rule of behavior. They have limited persistent memory and limited visibility range. We investigate the Filling problem in the asynchronous model.

We assume that the robots know an upper bound Δ on the maximum degree of the graph before entering. We present an algorithm solving the asynchronous Filling problem with robots having 1 hop visibility range, $O(\log \Delta)$ bits of persistent storage, and $\Delta + 4$ colors, including the color when the light is off. We analyze the algorithm in terms of asynchronous rounds, where a round means the smallest time interval in which each robot, which has not yet finished the algorithm, has been activated at least once. We show that this algorithm needs $O(n^2)$ asynchronous rounds. Our analysis provides the first asymptotic upper bound on the running time in terms of asynchronous rounds.

Then we show how the number of colors can be reduced to $O(1)$ at the cost of the running time. The algorithm with 1 hop visibility range, $O(\log \Delta)$ bits of persistent memory, and $O(1)$ colors needs $O(n^2 \log \Delta)$ rounds. We show how the running time can be improved by robots with a visibility range of 2 hops, $O(\log \Delta)$ bits of persistent memory, and $\Delta + 4$ colors (including the color when the light is off). We show that the algorithm needs $O(n)$ asynchronous rounds. Finally, we show how to extend our solution to the k-Door case, $k \geq 2$, by using $\Delta + k + 4$ colors, including the color when the light is off.

1 Introduction

In swarm robotics, a large number of autonomous mobile robots cooperate to achieve a complex goal. The robots of the swarm are simple, cheap, and compu-

* The research has been partially supported by the European Union, co-financed by the European Social Fund (EFOP-3.6.3-VEKOP-16-2017-00002).

tationally limited. They act according to local rules of behavior. Robot swarms can achieve high scalability, and cost-efficiency.

The Filling (or, Uniform Dispersal) problem was introduced by Hsiang et al. [2], where the robots enter an a priori unknown but connected area subdivided into pixels and have to disperse. At the end of the dispersion, each pixel has to be occupied by exactly one robot. We consider the Filling problem for autonomous, homogeneous, anonymous, myopic, silent, luminous robots on a connected graph in the asynchronous Look-Compute-Move (LCM) model. In this problem, robots enter a graph through a specific vertex, which is called the *Door* and must disperse to cover all vertices of the graph while avoiding collision, i.e. two or more robots can not be at the same vertex. When the Door vertex becomes empty, a new robot is placed there immediately. We assume that the robots know an upper bound Δ on the maximum degree of the graph.

We assume that, for each vertex v, the adjacent vertices are arranged in a fixed cyclic order. This cyclic order is only visible for robots at v, and it does not change during the dispersion. When a robot r arrives at vertex v from a vertex u, then the cyclic order of neighbors is used by r as a linear order of $\deg(v) - 1$ neighbors by cutting and removing u.

The robots act according to the Look-Compute-Move (LCM) model. In the asynchronous model (ASYNC), the robots activate independently after a finite but arbitrary long time, and perform their LCM cycles. Moreover, their LCM cycle length is not fixed.

The robots are *autonomous*, i.e. no central coordination is present, *homogeneous*, i.e. all the robots have the same capabilities and behaviors, *anonymous*, i.e. they cannot distinguish each other, *myopic*, i.e. they have limited visibility range, and *silent*, i.e. they have no communication capabilities and cannot directly talk to one another. However, *luminous* robots can communicate indirectly by using a light. Such robots have a light attached to them, which is externally visible by every robot in their visibility range. They can use a finite set of colors (including the color when the light is off) representing the value of a state variable. The robots are allowed to change these colors in their Compute phase.

2 Results

We describe a method, called PACK, which solves the problem by robots with 1 hop visibility range, $O(\log \Delta)$ bits of persistent memory, and $\Delta + 4$ colors for the single Door case, including the color when the light is off. We analyze the algorithm in terms of asynchronous rounds, where a round means the smallest time interval in which each robot, which has not yet finished the algorithm, has been activated at least once. Regarding asynchronous algorithms for the Filling problem, former works only guarantee termination within finite time. Our analysis provides the first asymptotic upper bound on the running time in terms of asynchronous rounds.

Theorem 1. *Algorithm PACK fills an area represented by a connected graph in the model by robots having a visibility range of* 1 *hop,* $O(\log \Delta)$ *bits of persistent storage, and* $\Delta+4$ *colors, including the color when the light is off. This algorithm needs* $O(n^2)$ *asynchronous rounds.*

We show how the number of colors can be reduced to $O(1)$ at the cost of running time. We encode the colours as a sequence of bits, which are then transmitted by a fixed alphabet of colours by emulating the Alternating Bit Protocol (ABP), also referred to as Stop-and-wait ARQ (see, e.g. [3]).

Theorem 2. *The modified PACK algorithm fills an area represented by a connected graph in the asynchronous model by robots having a visibility range of* 1*,* $O(\log \Delta)$ *bits of persistent storage and* $O(1)$ *colors. The algorithm needs* $O(n^2 \log \Delta)$ *asynchronous rounds.*

We show how the running time can be significantly improved by robots with a visibility range of 2 hops by presenting the algorithm called BLOCK.

Theorem 3. *The BLOCK algoritm fills the area represented by a connected graph in the asynchronous model by robots having a visibility range of* 2 *hops,* $O(\log \Delta)$ *bits of persistent storage, and using* $\Delta + 4$ *colors, including the color when the light is off. The algorithm needs* $O(n)$ *asynchronous rounds.*

We extend the BLOCK algorithm for solving the k-Door Filling problem, $k \geq 2$. We use the concept from [1] and assume that robots entering from different doors have distinct colors. We define a strict priority order on these colors to prevent collisions.

Theorem 4. *The extended BLOCK algorithm solves the* k*-Door Filling problem,* $k \geq 2$*, in the ASYNC model in finite time, with* 2 *hops of visibility,* $O(\log \Delta)$ *bits of memory and using* $\Delta + k + 4$ *colors including the color when the light is off.*

References

1. Barrameda, E.M., Das, S., Santoro, N.: Deployment of asynchronous robotic sensors in unknown orthogonal environments. In: 4th ALGOSENSORS 2008. pp. 125–140. LNCS 5389 (2008)
2. Hsiang, T., Arkin, E.M., Bender, M.A., Fekete, S.P., Mitchell, J.S.B.: Algorithms for rapidly dispersing robot swarms in unknown environments. Algorithmic Foundations of Robotics V, Springer Tracts in Advanced Robotics **7**, 77–93 (2004)
3. Tanenbaum, A.S., Wetherall, D.J.: Computer Networks. Prentice Hall Press, 5th edn. (2010)