On Fleet Size Optimization for Multi-Robot Frontier-Based Exploration

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Abstract

Exploring a terrain using a fleet of mobile robots is a key challenge that can be transposed to many real cases scenarios (e.g. mine clearance, search and rescue). Many researches have proposed some algorithms making the robots cooperate and optimize the overall exploration time. Given these algorithms, the problem is now to carefully determine the number of robots to use in a fleet. In this paper, we propose to address this question for the well-known frontier-based exploration algorithm proposed by Yamauchi. We report on the results of 6000 discrete simulations where we varied the size of the robot fleet, robots initial positions, as well as the number of obstacles in terrains of the same size.

1 Introduction

The multi-robot exploration issue has been addressed in the literature using different approaches and has been originally initiated by: [4] and [10]. This latter paper introduced a strategy named *frontier-based exploration* that inspired many other works. The postulate is the following: to speed up the exploration, a robot has to gain new information about the environment. Therefore, it has to move towards the boundary between open space and unexplored areas.

In order to speed up exploration even more while making it more robust against individual robot failure, Brian Yamauchi did propose to use a group of robots that exchange individual maps [11]. Each robot decides based on a local map where to go. Robots also cooperate by exchanging their maps.

Experiment conducted by Brian Yamauchi raises the following question: what is the optimal number of robots to perform frontier-based exploration of a terrain? By optimal, we mean a fleet size which minimizes:

- the **time** required to perform full terrain exploration, and
- the **costs** to acquire and run robots.

If 2 robots are likely to be faster than 1 robot to explore a given terrain, does this assumption applies to larger fleets? Regarding costs, they do increase with the fleet size. Obviously, the cost for acquiring a large fleet is higher than for a small one. But, what about operational costs that cover energy consumed by robots, human effort for administration and handling, as well as parts used for robots maintenance? The optimal number of robots is the one that allows "fast enough" exploration at a reasonable cost.

Finding the optimal size of a robotic fleet is not an easy question. There are several parameters that can impact the answer.

- Terrain size. Probably that more robots are required to quickly explore a large terrain than a smaller one.
- Obstacles density and shapes. In a terrain with many obstacles, there are less space to explore. On the other hand, navigation may be more complicated, especially with concave obstacles where deadlocks can occur or when multiple robots are located in the same area.
- The lie of the land. The exploration of a large single area takes probably less time than a terrain that decompose into few open areas, but connected with narrow corridors. In the latter, it is likely that robots might get in the way one for the other.
- Initial robots positions. Depending on the terrain and obstacles, locations of robots when on start up may impact the exploration duration and/or the cost.

In this paper, we study the optimal fleet size based on a series of simulations described in Section 2. We varied the size a fleet of homogenous robots that perform frontier-based exploration in a square terrain of fixed size with small convex obstacles uniformly placed on ground. Interestingly, measurements we collected show that both exploration duration and operation costs stabilize rather quickly. Section 3 describes and discusses these results. Last, we draw our conclusions in Section 4, and sketch some future works.

2 Simulations

In this section we describe simulations we conducted in order to figure out the optimal size of a fleet of homogeneous robots performing frontier-based exploration. We used our own discrete simulator BOSS[1] modeling the terrain as a square grid of 100x100 cells. A cell can be either empty or occupied by a fixed obstacle or a robot. Robots can move to any one of the 8 neighboring empty cells around their respective positions.

Figure 1 shows a screenshot of our simulator. The large window give a global view of the terrain being explored by 5 robots (blue dots). Robots close enough to communicate and hence share maps have a red line connecting them. Obstacle cells are colored in black. Unexplored cells are gray, explored ones are green except frontiers that are yellow. Around the terrain window, there are 5 small windows. Each of them displays the local map of a specific robot. The robot itself is shown as a red dot on its local map.

Initially, a robot only knows the terrain size and its location. On each simulation step, all robots are activated one after the other. When activated, a robot updates its own map of the

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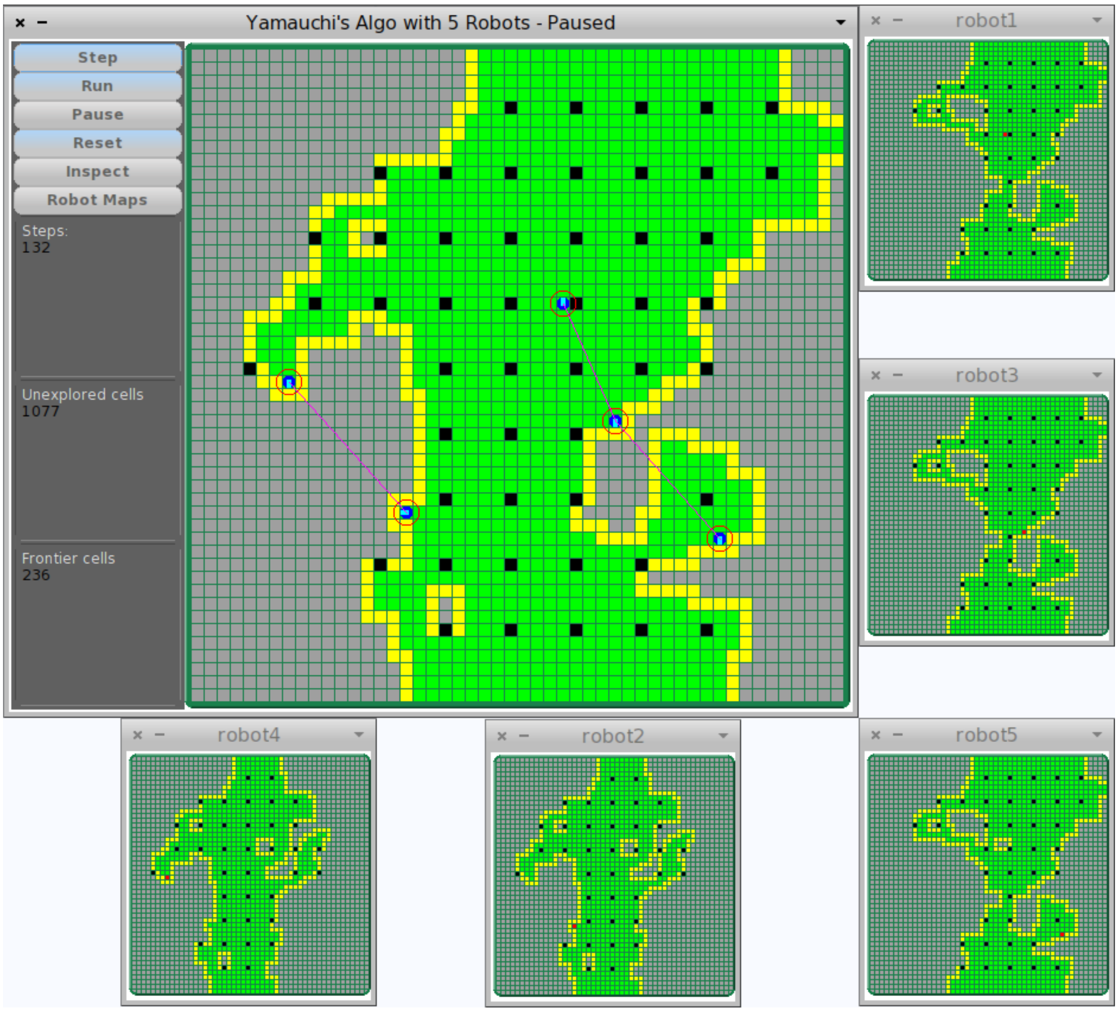
[1] roBOt Simulation in Smalltalk available under MIT license at http://car.mines-douai.fr/Boss/



Steps:
132

Unexplored cells
1077

Frontier cells
236

Figure 1: The BOSS Simulator

terrain based on data collected from a sensors belt that allows observing immediate 8 neighboring cells. Then, it computes a path towards the nearest frontier based on the $A - *$ algorithm avoiding all obstacles. Next the robot moves to the first cell in the path towards the selected frontier. The last action of a robot in a simulation step is to broadcast its map. Only robots within wireless range receive the broadcasted map and merge it to their own local maps. We diverge here from the experiment conducted by Brian Yamauchi where the 2 used robots could communicate all the time. We advocate that there are situations where robots cannot communicate simply because they are too far from each other, without mentioning obstacles that absorb electromagnetic waves.

In order to have a quite realistic simulation at least regarding the scale factors, we set the wireless range to 10 cells, given that a robot occupies one cell and it can explore immediate neighboring cells (at distance of 1). If we consider that each cell of our grid terrain is a square of 1m by 1m, we allow communications between robots that are at most 10m far from each other. The impact of obstacles on communications is ignored. Thus, in our simulations, robots can communicate if they are close enough regardless of the presence or the absence of obstacles in between.

Since we use Yamauchi's solution, map exchange is the only cooperative task done by robots. Each robot decides autonomously based on its local map where to go. Once the robot map is updated with sensed data and maps of neighbors, a robot selects the nearest frontier and moves toward it. At each simulation step, a robot moves one cell on a path computed using the A-Star algorithm. This path is recomputed every step, since the map is likely to evolve often.

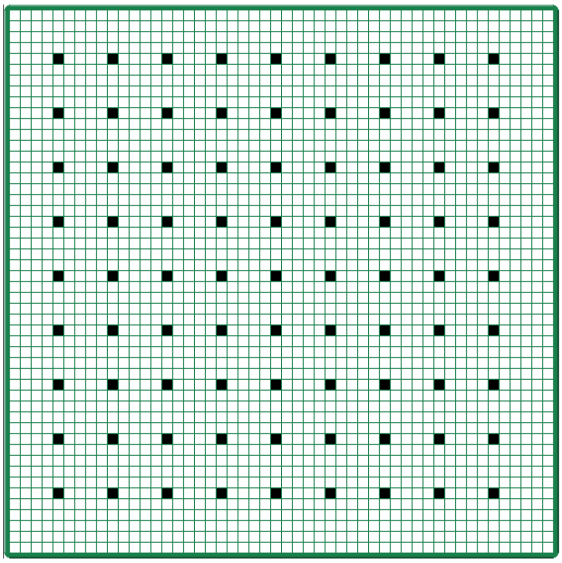


Figure 2: Checkerboard-like Terrain Used in our Simulations

We run two series of simulations with two square terrains of the same size of 100x100 cells. The first terrain was empty (no obstacle), while the other was a checkerboard-like terrain where 1 cell concave obstacles are located every 5 cells (see figure 2). We measured the number of steps required to have every empty cell of the terrain visited at least once for fleets of homogeneous robots.

The fleet size of exploring robots ranges from 1 to 100. Robots initial locations were chosen randomly among free cells. To filter out the impact of these initial locations, we performed 30 simulations for each fleet size. Results shown in Section 3 are based on average values of total steps to complete terrain exploration.

3 Results and Discussion

3.1 Simulation Results

Figure 3 shows the durations and costs for the 6000 simulations we performed. All values where converted to percentages to allow representing both durations and costs on the same graphic. Two curves correspond to durations and costs for 3000 simulations with different fleet sizes (30 per fleet size) performed in an empty terrain (no obstacle) of 10 000 cells. The two remaining curves represent again durations and costs for simulation performed in the same conditions except that the terrain contains 361 small obstacles, each occupying 1 cell.

Durations were measured in number of simulation steps. The duration percentage for a given fleet of size n is the number of steps to perform the exploration with n robots divided by the maximum duration to explore the terrain. This maximum is actually the number of steps required to complete the exploration with 1 robot.

$$durationPercentage(fleetSize) = \frac{duration(fleetSize)}{maxDuration}$$

The cost refers to the total energy consumed by the whole robotic fleet to perform the exploration. The cost percentage a given fleet of size n is the cost to perform the exploration with n robots divided by the maximum cost to complete the exploration. Simulations shows that this maximum cost is reached for a fleet composed of 30 to 45 robots.

$$costPercentage(fleetSize) = \frac{cost(fleetSize)}{maxCost}$$

We suppose that energy consumed for sensing and for communication is negligible compared to energy required for locomotion. Thus, the total energetic cost for exploring a terrain is proportional to the distance travelled by robots. Assuming that each robot moves by 1 cell on each simulation step, then number of cells travelled by a robot during a simulation corresponds to the number of steps to complete the simulation. So, the total energetic cost is approximatively the exploration duration multiplied by the number of robots.

$$cost(fleetSize) = fleetSize * duration(fleetSize)$$

3.2 Discussion

Our simulations confirm the initial intuition: the bigger the fleet of the robot is, the shorter is the exploration. This applies to both empty terrains and ones with obstacles uniformly distributed

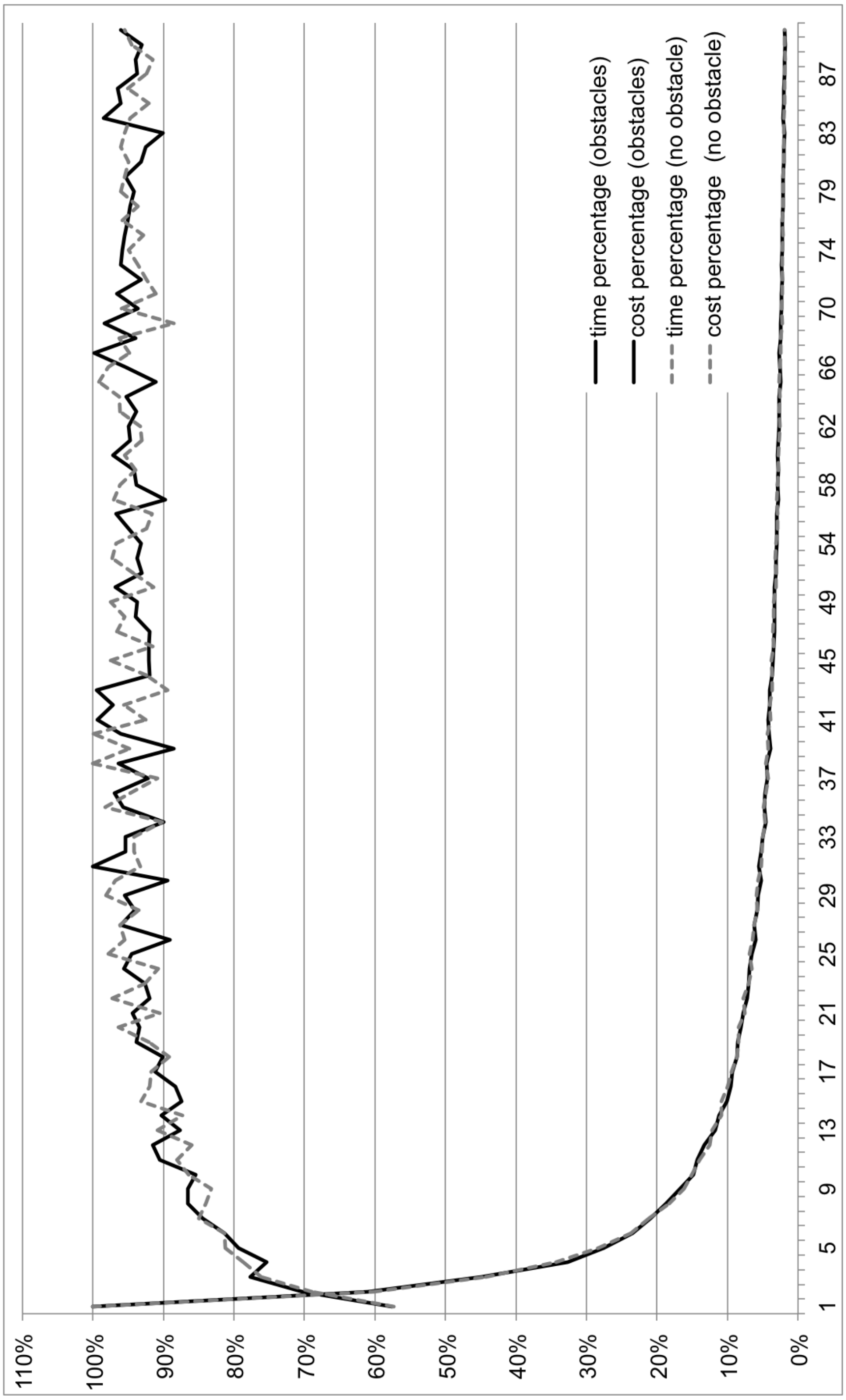


Figure 3: Durations and Costs Percentages for Simulations in Terrain with and Without Obstacles

(checkerboard-like terrain). There are very slight differences between both cases, even on Figure 4 which zooms in on the left part of Figure 3. The exploration duration quickly drops by approx. 80% for 7 robots, then flattens. So, regarding the exploration duration it does not worth it to use more than 15 robots, where the exploration is performed in 10% the time required to a single robot.

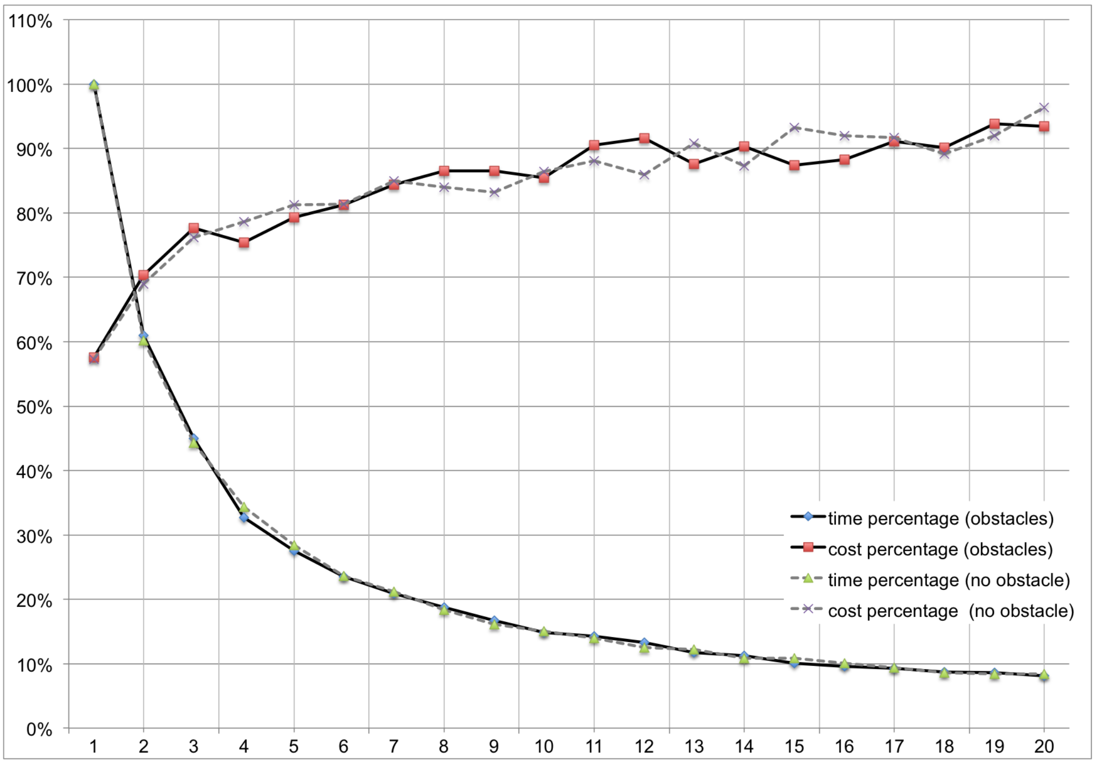


Figure 4: Durations and Costs Percentages for Fleet Sizes Up to 20 Robots

Regarding exploration cost, it increases with the number of robots. Interestingly, it flattens so it never exceeds the double energetic cost of using a single robot. An intriguing observation is that costs does not increase steadily, but instead oscillates. We assume that this is caused by a too weak collaboration among robots. Indeed, in Yamauchi's algorithm each robot decides alone on where to go. So, two close robots can compete to reach the same frontier. Some algorithms have been proposed to minimize this redundancy in frontier-based exploration such as in Stachniss' work [7] that uses a utility cost to assign target location to robots. Stachniss also provides simulation results to compare multi-robots exploration strategies with different number of robots. But his comparisons focus on the exploration time and aims at determining the most efficient algorithm while we are looking for the best fleet size for a specific algorithm taking into account the overall cost of the fleet.

4 Conclusion and Future Work

In this paper, we reported results of a series of discrete simulations on the exploration of a terrain with a fleet of robots. The exploration was driven by the frontiers between known area and unknown ones, based on Yamauchi's seminal work [10, 11]. As one might expect, the exploration time decreases when the number of robots increases. However, the duration curve flattens quickly. In our simulations in a 100x100 terrain, increasing the fleet size beyond 15 robots has little impact on the duration of exploration. Symmetrically, the energetic cost required to perform an exploration never exceeds the double cost for an exploration with a single robot. Thus, we can conclude that the optimal number of robots performing frontier-based exploration is approximately 15 for a 100x100 terrain with no obstacles or small concave ones uniformly distributed.

Regarding future work, there different interesting perspectives. An immediate follow up to the current paper is to carry on with frontier-based exploration and study the impact of different terrain sizes, as well as obstacle shapes, sizes and densities. The goal is to determine a function that gives the optimal number of robots knowing the terrain size. Actually, we expect, that there will be more than one function, because the obstacles densities, sizes and shapes are likely to impact the exploration duration and cost.

Another future work is to perform a similar study and determine the optimal robotic fleet size with alternative cooperation strategies such as [6, 3, 8, 5, 9, 2, 1]. This result, will enable us to actually compare the strategies. Eventually, we will be able to choose one strategy over another one depending on available knowledge on the terrain.

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