

Brick&Mortar: an on-line multi-agent exploration algorithm

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Abstract—When an emergency occurs within a building, it is critical to explore the area as fast as possible in order to find victims and identify hazards. We propose Brick&Mortar, an algorithm for the autonomous exploration of unknown terrains by a team of mobile nodes, referred to as *agents*. Because of the unreliability and short range of wireless communications in an indoor environment we suggest that agents communicate indirectly with each other by tagging the environment. Agents have no prior knowledge of the terrain map, but are able to coordinate in order to explore a variety of terrains with different topological features. In our experimental evaluation, we show that Brick&Mortar significantly outperforms the competing algorithms, namely Ants and Multiple Depth First Search, in terms of exploration time. The observed performance benefits suggest that our algorithm is suitable for safety-critical applications that require rapid area coverage for real-time event detection and response.

I. INTRODUCTION

Chemical, biological, radiological, nuclear and explosive (CBRNE) events refer to the uncontrolled release of chemicals, biological agents or radioactive contamination into the environment or explosions that cause widespread damage. CBRNE events can be caused by accidents or by terrorist acts. Although an event of this type could take place almost everywhere, the most challenging environment (and the one with the highest probability to occur) is on indoor environments, in a building or another highly frequented public place, such as a train station or the underground, as sadly demonstrated by the recent terrorist attacks in New York, Madrid and London.

Exploring all the area in the minimum amount of time and reporting back to the human personnel outside the building is an essential part of rescue operations. Such operations, however, may be obstructed by a number of limitations, e.g. the possible lack of a terrain map (the environment could anyway be heavily changed after a disaster), the failure of previously established networks, and the short-range and often unreliable wireless indoor communication. In addition, it might be difficult to use GPS positioning inside a building, so an agent cannot rely on knowledge of its exact location in the terrain, even if it were able to keep memory of its previous steps. In this paper, we take into account these limitations, and assume that agents can only rely on local information that is sensed in their vicinity (which other agents have left as a trace behind them), before making the next exploration step.

In this paper, we first analyze the functionality of two existing approaches to terrain exploration, namely Ants [1],

[2] and Depth First Search (DFS) [3], [15], [4], [10], which we modified to handle multiple robots (MDFS), and highlight their limitations. On the one hand, agents running the Ants algorithm cannot determine when the exploration task is completed. Moreover, whilst the first few agents are rapidly discovering new terrain, most of the remaining agents dwell on already explored network areas, leading to inefficient use of agent resources. On the other hand, agents running MDFS know when the exploration task terminates, but we show that they equally lack in coordination skills and often make poor use of resources.

Our novel algorithm, Brick&Mortar, overcomes the limitations of existing approaches, and offers significant performance gains in terms of exploration time for a variety of terrain topologies. Our experimental results allow us to understand the impact of several parameters on the performance of the three algorithms, including the number of agents, the terrain size, the numbers of rooms and the number of obstacles (e.g. desks or hazards in the middle of rooms).

The rest of the paper is organized as follows. Section II presents the assumptions of our model, and Section III provides a brief description of existing exploration algorithms and discusses their limitations. Section IV presents the new Brick&Mortar algorithm and discusses how it addresses the problem of agents traversing the same areas in loops. Section V presents a thorough experimental analysis of the three algorithms. An overview of related work is provided in Section VI, followed by conclusions and directions for future work in Section VII.

II. MODEL

In this section, we describe the model used by the proposed algorithm, Brick&Mortar, and the two competing approaches, Ants and Multiple Depth First Search, which we present in detail in Section III. We consider the task of exploring a hazardous terrain using a group of autonomous *agents*. The overall area is divided into square cells, some of them representing walls. In our model, walls are used to identify both real brick walls that constitute the building itself, and obstacles (e.g. victims) that agents cannot cross during their exploration phase.

A cell can be in one of the following states:

- *Wall*: The cell cannot be traversed by an agent because it is blocked by an obstacle, and any free space in it is not big enough to let an agent go past it.
- *Unexplored*: No agent has been in the cell yet.
- *Explored*: The cell has been traversed at least once, but the agents might need to go through it again in order to reach *unexplored* cells.

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- *Visited*: The agents have already explored the cell, and they do not need to go through it again to reach other cells. Conceptually it is equivalent to a *wall* cell, in that no agent is allowed to traverse it.

Agents are initially deployed in one of the boundary cells and, in each step, they are able to move from the current cell to one of the four adjacent cells in the North, East, South or West directions. As they move to an unexplored cell, they deploy a miniature device (e.g. mote or RFID) capable of storing small amounts of information about the state of the local cell. They also update the direction of this device, with respect to previously installed devices in adjacent cells. In indoor environments where GPS cannot be used, agents do not rely on knowledge of their exact location; once they find themselves within a cell, they can turn towards one of the four directions until they reach the next cell. Moreover, in emergency situations, long-range wireless communication may be intermittent and unreliable, so we assume that agents are able to communicate only by reading and updating the devices installed in the local and adjacent cells.

If agents are displaced from their current location, they are able to resume their operations in the new area where they land. We consider distributed exploration algorithms, in which agents make independent decisions about how to navigate through the terrain based on local state. When agents move from one cell to another, they annotate the device of the target cell with information that the traversed link is accessible by robots or humans. They also update the cell device with the length of the shortest accessible path (known so far) from a boundary cell to the current cell. When an agent discovers an event of interest in a cell, it sends this information wirelessly back to the human respondents via the shortest accessible path of cell devices; human respondents can then traverse the reverse path to reach the cell of interest.

III. EXISTING ALGORITHMS

Prior to presenting our Brick&Mortar algorithm, we give a brief description of two existing algorithms - Ants and Multiple Depth First Search - against which we test its performance in Section V. We also discuss some of their limitations that motivated us to design our new Brick&Mortar algorithm. To our knowledge, these are the only competing algorithms that do not rely on agents knowing their locations and the area map, and being able to establish reliable communication with each other. A detailed review of related techniques with slightly different assumptions is provided in Section VI.

A. Ants

We first discuss the behaviour, strengths and limitations of the Ants algorithm proposed in [1], [2]. This is a distributed algorithm that simulates a colony of ants leaving pheromone traces as they move in their environment [2]. Initially all cells are marked with value 0 to denote that they are *unexplored*. At each step, an agent reads the values of the four cells around it and chooses to step onto the least traversed cell (the one with the minimum value). Before moving there, it

updates the value of the current cell, for example by incrementing its value by one. The authors discuss a few other rules that could be used instead to mark a cell and navigate to the next one, but they all exhibit similar performance in terms of exploration time. Hence, we select the above variant of the Ants algorithm (move to the least visited cell) as a basis for comparison. The authors provide a proof that the agents will eventually cover the entire terrain (provided that it is not disconnected by wall cells).

The first advantage of the algorithm is its simplicity: agents do not require memory or radio communication, but only one-cell lookahead. Since they are easy to build, many of them can be used to shorten the coverage process. Secondly, there is no map stored inside the agents: if one of them is relocated (accidentally or on purpose) it will not even realize it and it will continue to do its work as if nothing happened. This means that the whole system is flexible and fault tolerant, and the area can be covered even if some markings or agents are lost. At the storage device of each cell, we only need to store an integer counting the number of times that agents have visited the cell.

The main limitation of the Ants algorithm is that the *visited* state is not used to mark the cells, so there is no way to tell when the environment is fully explored, and the agents continue the exploration phase until they run out of energy. Thus, this approach is not suitable in an emergency scenario, in which the primary consideration is to cover the overall area as soon as possible, and be notified immediately after the task is completed. Another limitation concerns the inadequate use of agent capabilities: in a scenario with many rooms most of the agents are busy sweeping the first few rooms repeatedly while only a few of them set out to explore new areas.

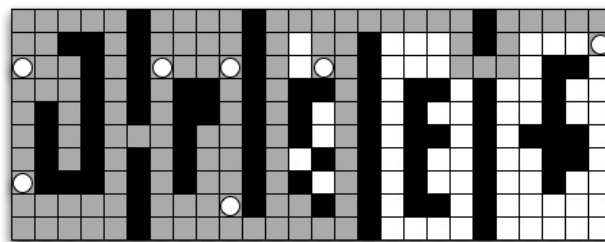


Fig. 1. The Ants algorithm is not efficient in a scenario with many rooms, because most of the agents explore the first rooms repeatedly, while only few of them set out to discover new areas.

B. Multiple Depth First Search

In order to address the limitations of the Ants algorithm, we consider a Depth First Search (DFS) approach to traversing the unknown terrain. DFS was first introduced in [3], and used for terrain exploration in [10], [4], [15]. In particular, in [15] the area is divided in smaller regions and a tree is built with each region as a node. The robots explore the tree using a centralized DFS algorithm. In [4] the authors propose an algorithm in which the area (with no obstacles

in it) is divided in cells and a single robot explores each cell using DFS. Finally, in [10] an algorithm is proposed in which multiple robots explore an area which is divided in cells. In this work, a DFS-like procedure is used by each robot to build spanning trees which are needed by the exploration algorithm.

In this section, we describe a concrete implementation of the algorithm for a scenario with many agents (Multiple Depth First Search, MDFS). Unlike Ants, MDFS allows agents to mark cells as *visited*, so that agents do not need to traverse them in the future. An agent knows that its task is completed if its four adjacent cells are either *visited* or *wall* cells.

The challenge in using more than one agent with this algorithm is to ensure that they can efficiently collaborate to explore the area. As each agent builds its own exploration tree, it marks *unexplored* cells as *explored* when it traverses a branch downwards, and it marks them as *visited* when it traverses a branch upwards (Algorithm 1). Each agent tries not to interfere with the trees of the other agents by marking *explored* cells with its own agent ID. When an agent finds itself at a cell surrounded by *explored* cells marked by another agent's ID (besides wall and visited cells), the current agent traverses the corridor of these *explored* cells trying to find an *unexplored* neighboring cell. If it finds one, it uses it as the root of a brand new tree that it starts covering with its own ID. Otherwise, if it becomes surrounded by *visited* or *wall* cells it terminates. MDFS requires $O(N)$ storage space at each cell, where N is the number of agents.

Using this algorithm the agents are typically able to explore the area in less time than using the Ants algorithm, and more importantly, each agent knows exactly when to stop its exploration task. Hence, the algorithm terminates when all agents stop moving, since when that happens all cells are marked as *visited* or *walls*.

Although the Multiple Depth First Search addresses some of the weaknesses of the Ants algorithm, it is still not very efficient in terms of exploration time. By definition it traverses each cell at least twice, thus resulting in a long exploration time even in open areas without walls where a single traversal would suffice. Another limitation of MDFS is that some of the agents may become surrounded by *visited* cells and stop exploring the area before the whole area has been covered, thus resulting in a waste of available resources.

IV. THE BRICK&MORTAR ALGORITHM

Our novel algorithm, named Brick&Mortar, is designed to address the weaknesses of the existing algorithms. Unlike the Ants algorithm, agents using Brick&Mortar know when the exploration task is completed and they do not spend much time revisiting the same cells. Unlike MDFS, they typically traverse each cell less than twice and they never get trapped within boundaries of *visited* cells.

The main idea behind Brick&Mortar is that of thickening the existing walls by progressively marking the cells that surround them as *visited*. Note that *visited* cells are equivalent to *wall* cells in that they can no longer be accessed. In the

Algorithm 1 Multiple Depth First Search

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1: if the current cell is unexplored then
2:   mark it as explored
3:   annotate the cell with your ID and the direction of the
     previous cell (parent cell)
4: end if
5: if there are unexplored cells around then
6:   go to one of them randomly
7: else
8:   if the current cell is marked with your ID then
9:     mark it as visited
10:    go to the parent cell
11:  else
12:    go to one of the explored cells randomly, avoiding
      selecting the cell from which you are coming unless
      it is the only candidate.
13:  end if
14: end if

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description of Brick&Mortar, we refer to *wall* and *visited* cells as inaccessible cells, and to *unexplored* or *explored* cells as accessible cells. Brick&Mortar aims to progressively thicken the blocks of inaccessible cells, whilst always keeping accessible cells connected. The latter can be achieved by maintaining corridors of *explored* cells that connect all *unexplored* parts of the network. The main rule that an agent must obey locally is never to mark the current cell as *visited* if, by doing so, it blocks the path between two accessible cells.

Like Ants and MDFS, Brick&Mortar does not require agents to know their location in the building. A relocated agent can simply navigate randomly until it finds an accessible cell and then continues the exploration from there. Brick&Mortar makes the blocks of inaccessible cells thicker until the entire terrain is converted to a large block of inaccessible cells. In a rectangular terrain without *wall* cells, agents starting from border cells always succeed in visiting the entire area. In more complex topologies with many rooms and obstacles, agents may be faced with a loop closure problem described below. We are now in a position to introduce the details of the proposed Brick&Mortar algorithm with and without loop closure.

A. Brick&Mortar without loop closure

The states of a cell are exactly the same as the ones used in the Multiple Depth First Search Algorithm and described in Section II. Brick&Mortar consists of two discrete steps detailed in the pseudocode below (Algorithm 2). In the *marking step*, the agent marks the current cell choosing between the *explored* and *visited* states. In the *navigation step*, the agent decides which cell to go to next giving priority to the *unexplored* cells around it.

In the marking step the agent updates the state of the current cell, choosing between the *explored* and *visited* states. The cell is marked as *visited* only if it is not blocking the way between two accessible (*explored* or *unexplored*) cells (say *A*

(*visited* or *wall*) cells without having succeeded in marking the entire loop as *visited*. In order to avoid being trapped, loop resolution is performed in four phases discussed below:

- **Loop detection:** Initially, an agent follows the marking and navigation steps described in Section IV-A leaving a trace in each cell that it traverses (how it moved out of it), until it detects a loop. This happens when it moves into the same *explored* cell a second time (but not in the opposite direction than the one used previously to move out of that cell). Upon detecting a loop, the agent moves to the loop control phase. The loop detection phase requires $O(N)$ storage capacity at each cell, where N is the number of agents.
- **Loop control:** To take control of the loop, an agent A starts traversing the loop a second time in the same direction, trying to take control of each cell by annotating it with its own agent ID_A (this requires $\log N$ bits, where N is the number of agents). It is possible only if the cell is explored and it is not already annotated with another agent's ID (say ID_B). Agent A knows that it has succeeded in taking control of all cells in the loop when it steps again on a cell that is already annotated with the same ID. In this case, it immediately switches to the loop closing phase.
- **Loop closing:** The agent is now in a position to break the loop by marking the current cell as *visited*, and continuing to do so until it reaches the first intersection (the cell with at least one *explored* neighbor cell that does not belong in the loop). The agent then switches to the loop cleaning phase.
- **Loop cleaning:** The agent removes any traces of the loop control phase, by moving backwards in the loop, removing its ID from the cells that it previously annotated, and resetting the direction in which the agent moved out of the cells to null.

It remains to describe in detail what happens in the loop control phase when an agent A is not able to take control of a cell, either because the cell is already *visited*, or because it is being controlled by another agent B . To deal with this scenario, we allow agents to interrupt the loop control phase, either permanently or temporarily. In the former case, an agent literally quits the loop resolution mechanism and moves to the loop cleaning phase. In the latter case, the agent can wait at a cell, as a *standby* agent, until the state of the cell is changed. In what follows, we provide specific rules that define how an agent decides whether to continue, quit or stall controlling cells with its ID during the loop control phase. Let agent A try to move to the next cell in order to control it (i.e. to annotate it with ID_A). The decision it makes depends on the state in which it finds the cell:

$$\left\{ \begin{array}{ll} \text{control cell,} & \text{if cell explored without control} \\ \text{start loop cleaning,} & \text{if cell visited} \\ \text{start loop cleaning,} & \text{if } B \text{ controls \& } (ID_B > ID_A) \\ \text{start loop cleaning,} & \text{if } C \text{ standby \& } (ID_C > ID_A) \\ \text{become standby,} & \text{otherwise} \end{array} \right.$$

We finally need to define how, a standby agent (which

waits at a cell as a result of following the last branch above), reacts to changes in the cells state. The rules that determine its behavior are:

$$\left\{ \begin{array}{ll} \text{start loop cleaning,} & \text{if replaced by another ag.} \\ \text{start loop cleaning,} & \text{if cell becomes visited} \\ \text{continue loop control,} & \text{if cell is cleaned} \\ \text{remain standby,} & \text{otherwise} \end{array} \right.$$

An agent that manages to complete its loop control phase has succeeded in controlling *all common cells with other interfering loops*. It performs loop closing, and then cleans all common cells, before another interfering agent gets the opportunity to take control of them. Hence, although in general loops are handled concurrently, agents are able to detect when their loops interfere, and in this case, they resolve them in a sequential manner. The loop control phase has a similar role as locks in database systems, i.e. it allows concurrent operations whilst leaving the system in a *consistent* state. In our case, consistency means that all *explored* and *unexplored* cells remain connected, and no agent is trapped within *visited* cells.

Using the rules above we can prove that when agents try to resolve overlapping loops, they never cause a deadlock, they never get trapped within *visited* areas, and they always terminate (the proof is omitted for space reasons). However, to ensure this we require memory capacity at each cell that grows linearly in the number of agents (similar to MDFS storage requirements). In the future, we plan to investigate ways of adjusting our algorithm to require a fixed amount of storage space (like Ants).

V. SIMULATION RESULTS

We developed a simulation tool to test the performance of Brick&Mortar and the competing algorithms (Ants and MDFS), which allows us to automatically generate terrain maps with different topological features (by changing input terrain size, number of rooms, number of obstacles, etc.). The tool can be instructed to run any of the algorithms with different numbers of agents on a variety of maps.

In the results presented below, we study the impact of i) the number of agents, ii) the terrain size, iii) the number of rooms, and iv) the number of obstacles (that generate loops) on the performance of the three algorithms. Each point in the graphs is the average of running an algorithm 20 times, each time with a different map that satisfies the input topological features. In each experiment we vary the values of one parameter, and assign default values to the remaining ones. The default values are: a map of 2500 (50 by 50) cells with 30 obstacles and 36 (6x6) rooms, which is explored by 20 agents. The agents are deployed from the top left cell of the area. We consider two performance metrics: i) the *exploration time* (black lines), i.e. the number of steps it takes for the agents to traverse all cells of the map at least once, which can be measured for all three algorithms; and ii) the *visiting time* (grey lines), i.e. number of steps that it takes for all agents to determine that they have completed the exploration task. The latter can only be measured for

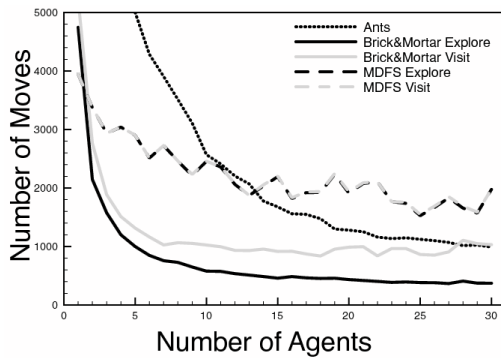


Fig. 3. Effects of changing the number of agents in the team

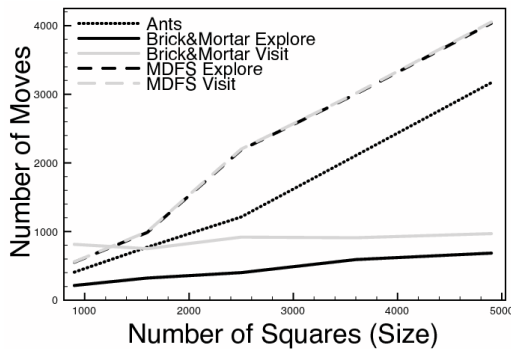


Fig. 4. Effects of changing the size of the map

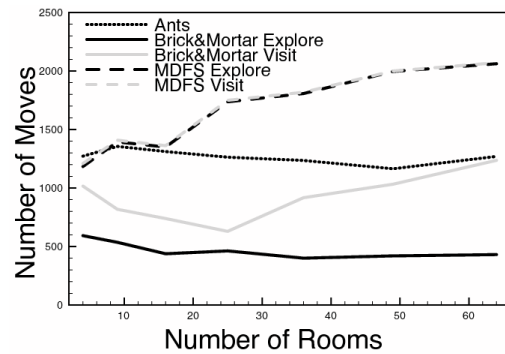


Fig. 5. Effects of changing the number of rooms in the map

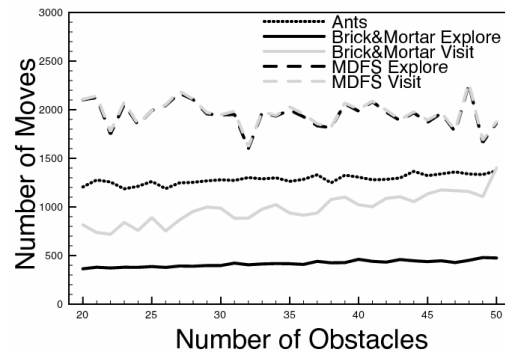


Fig. 6. Effects of changing the number of obstacles in the map

Brick&Mortar and MDFS, since agents running the Ants algorithm cannot determine when they terminate.

Effect of agents: Figure 3 shows that Ants always underutilizes agent resources compared to Brick&Mortar, but as the number of agents increases it becomes faster than MDFS. The MDFS algorithm is the least sensitive to varying the number of agents, which is owed to the fact that agents become trapped early on within visited cells and are unable to help cover new areas. Brick&Mortar uses efficiently up to 15 agents, beyond which point it does not improve much, owing to the fact that agents interfere with each other trying to resolve the same loops. Observe that the gap between the exploration and visiting time of Brick&Mortar increases with the number of agents. When more agents are available, they manage to speed up traversing the cells at least once, but they cannot do much to speed up loop closure and terminate early. In the future, we plan to study how we could achieve better load balancing by dispersing agents to enter the network from different cells.

Effect of area size: Figure 4 shows that Brick&Mortar scales gracefully as the area size increases. For areas of up to 4,900 cells, MDFS is 8 times slower and Ants 6 times slower than Brick&Mortar in terms of exploration time; similarly, MDFS is 4 times slower in terms of visiting time.

Effect of rooms: Figure 5 shows that as we increase the number of rooms the exploration time of the Ants and Brick&Mortar algorithms are not significantly affected, whereas the exploration time of MDFS becomes 2 times

slower from 4 to 64 rooms. For an area of 40 rooms the exploration time of Brick&Mortar is half its visiting time, which means that the task is completed way before the agents know it. In all cases, Brick&Mortar outperforms the two competing approaches by factors of 3 or 4, both in terms of exploration and visiting time.

Effect of obstacles (wall cells that cause loops): Figure 6 demonstrates the impact of obstacles (and therefore loops) on the performance of the three algorithms. We observe that Ants and MDFS are not particularly affected by the presence of loops, whereas the visiting time of Brick&Mortar increases linearly in the number of obstacles. Hence in certain environments with a very large number of obstacles, it might be worth using one of the competing approaches, or a hybrid algorithm in which an agent starts with Brick&Mortar and switches to Ants or MDFS upon detecting a loop. We leave the study of hybrid algorithms to future work.

VI. RELATED WORK

Choset [6] provides a survey of coverage algorithms and distinguishes them into *off-line* and *on-line*. In the former the agents are previously provided with a map of the area to explore, while in the latter, also called *sensor-based*, no assumption is made concerning the availability of an environmental map for the agents. Zheng et al. [7] prove that the original problem is NP-complete, and propose a polynomial algorithm that yields a solution at most eight times slower than the optimal solution. Agmon et al. [8]

propose a faster tree construction algorithm, while Hazon et al. [9], [10] focus on the robustness of the solution, so that even if only one robot remains in operation, it will be able to carry and complete the exploration task. Our Brick&Mortar algorithm differs from these approaches because it considers the on-line problem, i.e. it does not rely on the knowledge of the terrain's map. The ants-inspired algorithm [1], [2] divides the area into square grid cells on which the exploring agents leave traces of their passage, similarly to real ants leaving pheromone. This algorithm is already described in detail in Section III. A similar approach to the Ants algorithm uses a sensor network infrastructure to provide agents with information about the visited areas and direct them to the least recently visited direction [11]. Kong et al. [12] propose an algorithm that explores an area in forward and reverse phases. The idea is to gradually build a graph of the environment which is shared by all the robots of the team. Yamauchi presents a frontier-based exploration algorithm [13], where the agents explore the environment, represented by a regular grid of cells, keeping in their memory a map of the area and always directing themselves "to the boundary between open space and uncharted territory". A depth first search algorithm is used to move from the current position to the next frontier. The algorithm also makes the same strong assumptions as in [12], namely perfect localization and reliable communication among agents. Burgard et al. do not assume that the environment is divided into grid cells [14]. Agents compute a utility function to go to the next "frontier" in order to maximize the explored territory. Rekleitis et al. [15] try to improve the exploration by mapping the environment while the area is covered by two robots. Batalin et al. [16] focus on agent dispersion and propose two algorithms to make the agents move away from each other when they are in sensing range. Finally, Howard et al. [5] present a general approach to exploring a building, finding objectives and reporting them back to the human personnel outside. However, it requires human support to solve problems like loop closures or map merging between the agents so it does not satisfy the requirements for autonomous area coverage.

VII. CONCLUSION AND FUTURE WORK

In this paper, we proposed a new algorithm called Brick&Mortar, for the multi-agent exploration of unknown terrains. Agents running our algorithm can easily determine when the exploration task is completed. Our algorithm avoids exploring the same areas multiple times, it makes good utilization of all agents and it is capable of resolving loops. The experiments show that our algorithm is significantly faster than the two competing algorithms, Ants and Multiple Depth First Search, in a variety of scenarios.

In the future we would like to explore in detail how to use cell devices as a network infrastructure, in order to communicate interesting events back to human responders and assist them in finding the cells where events were detected. Another challenge is to cope with unexpected events like collapsing walls that block some of the cells, or relocation of agents to different parts of the terrain (e.g.

by the rescue team). Finally, mobile nodes could leverage their limited storage capabilities to maintain partial views of the terrain's map in their memory. Once they are within communication range, they could collaborate by carefully merging their inaccurate and possibly inconsistent maps.

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