Review of Grid Navigation Research in the Context of Emergency Routing

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Abstract

Grid-based navigation is one important approach for path finding besides the more often used network navigation. This paper makes a review of different approaches of grid navigation in the context of emergency routing, for grid navigation has many advantageous aspects and could be applied for indoor navigation in emergency routing. We also identify several future research directions for grid navigation applying in the emergency routing.

1 Introduction

As the emergency responding needs a path plan to guide the responders like fire fighters to the hazard scene, we have to consider the introduction of some navigation technology to support the emergency response. One promising candidate for this task is the grid navigation, which is currently used in the field of robotics navigation, computer game and simulation of human movement, indoor and outdoor human navigation. We may find grid-based navigation also essential for the emergency routing, such as directing a fire-fighting robot to explore a room on fire and utilizing the emergency simulation for training fire fighters. Therefore, we review
the current grid navigation approaches, point out gaps in existing research and propose future developing trend of grid navigation for emergency routing.

Grid navigation is defined as “a navigation system related to a reference grid instead of the true north for the measurement of angles” (Parker 2003). Although this definition may not be strictly followed in the real work, we can still perceive that only the research contributions that represent the route environment in lattice form and utilize these lattices to finish the path-finding task could be labelled as “grid navigation related works”. From this point of view, we organize the current grid navigation approaches into three main categories. They are grid navigation in the robotics field, computer game and simulation of human movement field, and indoor/outdoor human navigation field. The review of papers is organized with respect to this categorization.

The paper is organized as follows: in this section, we formulate the three categories with the context of emergency routing. In the second section, a comparison of the three main categories of grid navigation is provided. In the third section, we discuss the applicability of current grid navigation approaches in emergency routing. Finally, we shortly conclude the grid navigation development and propose research targets for addressing the grid navigation need in a complex public building under emergency situations.

1.1 Robotics approaches

The robot navigation is among the key part of a robot system to allow robot to operate in specific environment, and is also important for emergency routing. For example, when the fire and plume block several floors of the building, we have to rely on fire-fighting robots to search and rescue the survivors in this area.

Robots move in a style quite different from human beings. Human can perceive the surrounding environment fast in a unique cognitive way. On the contrary, robots have to clearly address many issues to gain the navigation ability. The first issue is how to utilize sensors to scan the surrounding environment and keep the scanned data in the robot storage system (Lidoris et al 2009). The second problem is how to locate the robot position in the scanned environment to provide the start position of the navigation route. Thirdly, after the path plan is generated, the robot still has to control its velocity and posture to follow this plan and avoid collisions with obstacles. Besides these topics, there is another crucial issue existing in the whole navigation process for robots. That is how to address the dynamic feature of the emergency navigation environment. The clue for solving all these problems could be found in the existing robot navigation approaches.

The localization and position task for robot in the emergency scene could be tackled by the Simultaneously Localisation and Mapping (SLAM) solution proposed by Smith et al and Durrant-Whyte (Smith and Cheeseman 1986, Smith et al 1990, Leonard and Durrant-Whyte 1991). These pioneer SLAM works provide a foundational theory that defines how a robot could recognize the surrounding environment and locate its own position in this environment. In order to finish the navigation task, SLAM needs to be combined with the “occupancy grid” method
to organize the acquired traversable information by robot sensors from the environment (Elfes 1987, Elfes and Matthies 1987, Elfes 1989) (Figure 1).

![Figure 1: (a) The occupancy map generated by the sonar sensors of robot; (b) the multiple application axis of this map (from the work of Elfes 1987).](image)

During the emergency management, it is common that not complete navigation information of the environment is available, and robots have to acquire some navigation data by their own. Thus a solution to generate workable paths with occlusion is proposed (Saitoh et al 2009). This solution firstly initializes current unknown area for sensors with an intermediate moving cost value to secure the existence of an autonomous drivable path, and secondly updates the routing environment with the new sensor information to receive a true optimized path. There is another interesting navigation approach that utilizes the theory of physical diffusion to handle the uncertain routing environment for robot (Stopp and Riethmuller 1995).

Providing flexible navigation path to robot is indispensible for the emergency routing, as the previous generated path plan could be unfeasible during emergency development. One option is to introduce the level-of-detail idea into the robot grid navigation, and the robot could receive both a nearly-optimized path and a minimum routing cost of computing resource (Figure 2) (Hornung and Bennewitz 2012). Another option is to produce a mixed navigation route, which provides path segments in a topological graph form in the safe area and path segments in metric description in the hazard spreading area (Thrun and Bücken 1996, Konolige et al 2011).
The context-related social costs concerned by human beings are also crucial to allow the robot working in an emergency scenes with people activity like fireman and evacuating people (Kruse et al 2012). Therefore, we have to analyze the human behavior in depth, such as people would reduce the velocity of movement instead of adapting path when possible collision among them would happen. Only with this knowledge robots could predict the next movement of human and avoid collision with a move efficient alternative path.

There also exist approaches that consider the introduction of 3D voxel grids to improve the robot navigation performance. These efforts enable the robot to function properly in an emergency scene with many irregular 3D obstacles (Marder-Eppstein et al 2010, Kläß et al 2012). In these solutions, the voxel map could be provided by committing a ray-surfel intersection detection algorithm on the 3D environment (Figure 3a, b).

Figure 2: (a) A grid-based optimized path for the experiment area; (b) a footstep path for the same area; (c) an adaptive level-of-detail path for the same area (from the work of Hornung and Bennewitz 2012).

Figure 3: (a) Voxel and 2D occupancy grid demonstration for an office; (b) three typical scenes of voxel occupancy by detecting the relationship between its passing ray and containing surfel (from the work of Kläß et al 2012).
When the hazard covers the space surrounding the building, we have to supply the robot with the outdoor navigation information. Thus, the robot grid navigation should also consider several traversability-related elements for robot moving on rough outdoor terrains (Chilian and Hirschmuller 2009, Neuhaus et al 2009). And we have to evaluate the DEM data from the point of the degree of danger for robot movement, which is a weighted sum of the slope value, roughness value and step height value in the environment (Figure 4).

![Figure 4: (a) DEM of the experiment area; (b-e) danger value and its composing elements value for the example area (from the work of Chilian and Hirschmuller 2009)](image)

### 1.2 Computer game and simulation of human movement approach

Besides the grid navigation application in robot field, there also exists a major grid navigation developing approach in the field of computer game and simulation for human movement. These research contributions could be utilized to build the virtual reality training system for fire brigade by using 3D gaming technology or to analyze the evacuation routing plan by executing an emergency simulation program for specific building.

This approach has many similarities and differences with the robot navigation approach and human navigation approach. On the one hand, during the simulation or game playing, because of human motion simulated nature, the agents or game characters could move more like real human than robots. For example, the agents or characters can climb up the low obstacles or even crawl through the wholes on walls if allowed. On the other hand, all these moving ability and the collision avoidance have to be explicitly defined during the program design process, for the activities of simulated agent or animated character are totally controlled by corresponding codes. Furthermore, the proper solution for changing between known environment and unknown environment is also appreciated in this approach. It is common that in an emergency simulation a former passable path will become unfeasible to use, when an expected fires appears.

A typical research topic in this field is to project all the obstacles of the animated scene to a 2D bitmap to accelerate the process of forming path plan (Kuffner 1998). But this method lacks many other important navigation elements in emerg-
ergency simulation, such as the simulated vision and character movement along Z axis.

The game map research contributions could also be taken to improve the path-finding efficiency on emergency routing maps (Björnsson and Halldórsson 2006). We can use both the research fruit along this trend, such as the “dead-end” heuristic algorithm and the “gateway” heuristic algorithm. The first algorithm eliminates the map regions not used for the specific routing operation before executing path-finding; the second algorithm introduces connecting areas between separate map regions to reduce the computing cost of routing (Figure 5). Besides improving the routing algorithms, the introduction of hierarchical data structure to large scale grid maps is also required in emergency routing (Botea et al 2004). Because using multi-level indexes for the large grid map could minimize the path-finding area, and accelerate the routing speed for specific request.

![Figure 5: (a) (b) Using dead-end heuristic algorithm and gateway heuristic algorithm for the same navigation task on a game map (from the work of Björnsson and Halldórsson 2006).](image)

To mimic the human action in the emergency scene, committing human motion simulation is also crucial (Bandi and Thalmann 1998). In order to do this, we have to discuss many important topics affecting motion simulation for humans, such as the “forbidden region” and borders of holes in the navigation simulation (Figure 6). More important, we have to clearly formulate why some path results generated without considering these restricted areas are not feasible under the complex 3D emergency situation.
1.3 Indoor and outdoor navigation for human approach

As is well known, human are intelligent and able to solve the navigation problem more easily than robots or simulated agents. For example, people can fast change kinematic posture according to the dynamic routing situation, such as jumping over unexpected ground obstacles without reducing the moving speed. Under most
situations, all these actions are only feasible for human body instead of robots and simulated agents. Moreover, people can also adapt their route flexibly according to the changing environment. For example, they can easily perceive which route will lead to a dead end with the emergency development and quickly abandon this route, compared to the robots or simulation program searching to the dead end and then turning back.

With a unique intelligent and kinematic ability, people usually only need crucial path information like significant directional change between path segments to adjust their map in mind and solve all the unexpected problems along movement by their own. Nevertheless, this does not mean we could ignore the requirements from some special groups of people, such as blind people and wheelchair using people.

Public buildings like supermarket and office draw attention of the navigation researchers. There is a navigation solution for supermarket that could be used to implement the emergency evacuation guide. It utilizes a grid map of the supermarket and user positions located by WiFi signal strength to finish the routing job, and takes a handset to guide users with voice instructions during the movement (Bhattacharya et al 2011). For the emergency evacuation in the office, we could use a 3D-to-2D projection to receive the floor grid plan, and applied the context-relative searching technology to construct the optimized path and simplify the preliminary path result (Lyardet et al 2006).

Besides the 2D-projection navigation solution, we should also introduce the 3D object to indoor emergency navigation to more accurately describe the route environment, and receive an evacuation path by considering the 3D shape of obstacles. The usage of virtual 3D bricks originated from the famous toy vendor “LEGO” may be sounding to properly organize the indoor navigation space(Figure 8) (Yuan and Schneider 2010). Although this model is successful on introducing the effect of width and height of user into navigation consideration, it still has some limitations on providing workable moving plans for disabled people.

When emergency spreads to the building surrounding area, the navigation assistant for people in large outdoor space is also necessary. Unlike the limited space of the indoor environment, the outdoor space normally has a larger spatial coverage. Therefore, how to efficiently subdivide the outdoor space is crucial. For navigation on a middle spatial scale, Bemmelen et al. provided an extended raster approach to finish the navigation tasks for cross-country movement (Bemmelen et al 1993). This method abandons the usage of center node to represent each raster cell during the path-finding process and received a better route than classical solution (Figure 9). For navigation on a global scale, Stefanakis and Kavouras utilize square grids or triangular grids in tessellations to solve the path-finding problems (Stefanakis and Kavouras 1995). The implementation of this solution divides the routing space to a graph containing finite spots, and then initialize each spot with the accumulated moving cost from the start position. Thus, the path-finding problem is translated into a weighted graph searching question.
2 Comparison between the different approaches

The three main application fields of grid navigation have their own features, and this could attribute to the difference of their central research target. The robotics navigation has used the metric grid in the routing process most frequently, because robot needs to periodically update the routing environment data and control the body to follow the free space to avoid collisions with obstacles. The grid navigation of computer game and simulation for human movement also needs a fine grid subdivision of the environment to avoid obstacles. Thus, by using grid the agents or characters in programs will behave more like humans to change their route, when possible collision would happen.
Whilst the application pattern of grid in the field of indoor and outdoor navigation for people are quite different from the two previous fields. The reason is that people naturally have the ability to handle the posture control and collision avoidance with ease. Thus they only need a coarse route guidance, which could provide key information along the optimized path. Therefore, the provided route for people only need to cover the important path segment changes like turnings of route.

Besides the different research target for three main fields, there are many other differences existing on spatial scale, route accuracy, human-based optimization and interactivity between the navigation and dynamic environments. The divergence of three fields is likely to continue existing.

Although three fields differ significantly by nature, they can also share same advanced technologies for grid navigation in emergency routing. For example, with the intention to behave more like human, the robotics research and simulation research tend to introduce the social cost field of humans in their navigation process; the navigation for human also tends to evaluate the step limitations of blind people or wheelchair users, which are commonly considered in the robotics and simulation navigation research.

3 Applicability for emergency response

The current approaches of grid navigation are successful on addressing many path-finding problems in the robot field, simulation field and human navigation field. Nevertheless, there is still room for improvement of grid navigation to the emergency response. According to our understanding, there exist two main issues for applying current grid navigation approaches in emergency response.

The first issue is the insufficient research of current grid navigations to meet the dynamic demand of path-finding in changing environments. We have observed that the current approaches by robotics research applied a preliminary solution to consider several dynamic routing restrictions in the environment, such as a simple changeable occupancy attribute of the grid (Stopp and Riethmuller 1995, Thrun and Bücken 1996, Saitoh et al 2009, Hornung and Bennewitz 2012). Nevertheless, a large amount of these solutions do not properly handle the all dynamic element in emergency routing, for example quickly changing environments as the activity of people or obstacles quickly moved by wind waters, etc. For example, during the robot navigation if a person currently stands in one grid and soon move to another grid, should we assign the two related grids with free attribute or occupied attribute? Besides the insufficient consideration of fast moving obstacles, the research focuses on the static state of restricted regions in the surrounding environment. For this reason, the “update” meaning for routing environment generally equals to reset new cost values for grids that are blocked by obstacles or just around the corner in the previous environment scanning (Stopp and Riethmuller 1995, Marder-Eppstein et al 2010, Hornung and Bennewitz 2012). Thus these solutions could not face the routing problems in changing-state environment, such as a scene with the increasing impassable area caused by the fire spreading in buildings.
What can be learned from the analysis of the inefficiency of path-finding solutions under dynamic emergency situations is that the consideration of multiple changing elements in the navigation process is required. According to our view, we have to add both the local variable navigation element like people activity and global variable navigation element like emergency spreading in the routing environment. Thus, we have to introduce a modifiable moving cost that will place a dynamic weight on route evaluation and produce a flexible route result, which could update path segments with the emergency development. Furthermore, according to the non-navigation-expert feature of most emergency responders, this dynamic path result also has to be produced by adapting the formerly-generated optimized path instead of directly re-planning a whole new path, when the previous route is not feasible (Kruse et al 2012).

The second issue, which draws attention of the grid navigation research for emergency response, is how grid navigation could use efficient data structures to hold the routing data generated by scanners from the real 3D world. Due to that the complex 3D world could bring a large volume of navigation data. The solution for this issue may cover two key topics. They are the usage of 3D hierarchical data structure and a promising subdivision method of the routing environment data.

In our opinion, the introduction of 3D hierarchical data structure could provide us with a more efficient organization for routing data. Unfortunately, mere preliminary structures for 3D grid data organization in navigation are observed (Neuhaus et al 2009, Marder-Eppstein et al 2010, Kläß et al 2012). We believe that a promising 3D hierarchical data structure should be neither a simple array to hold the accessible state of voxels, nor an oversize data object to store more grid attributes than navigation need. This is because an array could only keep over-simplified occupancy information. And the usage of a data object with non-navigation grid information like geometric representation would probably bring a significant increase on storage space consumption. Therefore, what we suggest is a data structure that could hold both the position of each grid and a proper amount of additional route-related information like the degree of traversability in every grid.

The efficient organization of the 3D routing data also contains the proper subdivision of the routing scene. After a careful study of the current works, we have perceived that the word “subdivision” really has two meanings in the grid navigation (Bemmelen et al 1993, Stefanakis and Kavouras 1995, Thrun and Bücken 1996, Botea et al 2004, Björnsson and Halldórsson 2006; Lyardet et al 2006, Yuan and Schneider 2010). The first meaning is to tessellate the whole routing environment with specific types of grid, such as triangles and squares; and the second meaning is to aggregate the tessellation result of the first level to generate a spatial index. Only a very limited number of approaches implement the voxel tessellation of 3D environment (Bandi and Thalmann 1998, Yuan and Schneider 2010), and no mature solution for efficiently organizing large number of 3D grids into spatial indexes are observed.

We believe the quality of research on these two key topics directly determines the success for the future development of the grid navigation for emergency routing. Thus we try to propose three promising future research topics to overcome these limitations in Table 1.
There are still more topics that needs to be covered in order to allow the navigation application to be operational under emergency situation. For example, how to provide the emergency responders like fireman with fast navigation data support? To answer this question, firstly we may have to locate the position of fireman, and secondly fetch the specific amount of the navigation information to this fireman to finish search and rescue task. Another issue is how to re-discover the former known environment with hazard spreading like a building floor being filled with fires and plume. Under this situation, the fireman may need some portable sensors to update the existing grid map in order to search for survivors (Ramirez et al 2009).

4 Conclusion and future work

The distinctions in research target and application field finally determine the different developing trend of the grid navigation in the robotics, computer simulation and navigation guide for human. Nevertheless, they still can face same bottlenecks when applied for indoor navigation in case of emergencies. What we believe is that they will exchange some key technologies and keep their unique features in such a way that the emergency routing will take benefits from all of them.

Applied for emergency response grid navigation will need to consider larger and more complex environments as in real cities. This implies that approaches for grid navigation should consider several additional aspects:

- hierarchical 3D data structures to organize grid. The grid in whole building may become very complex and will require a sort of 3D levels-of-detail approach for fast computation;
- Subdivision method for complex routing environment. Complex buildings with many obstacles will require a dedicated method for surface gridding.

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<th>Solutions</th>
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<tr>
<td>Dynamic routing environment</td>
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<tr>
<td>Large volume of 3D grid data</td>
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