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Multi-agent based path planning for first responders among moving obstacles

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ABSTRACT

Natural or man-made disasters can cause different kinds of moving obstacles (e.g., fires, plumes, floods), which make some parts of the road network temporarily unavailable. After such incidents occur, responders have to go to different destinations to perform their tasks in the environment affected by the disaster. Therefore they need a path planner that is capable of dealing with such moving obstacles, as well as generating and coordinating their routes quickly and efficiently. In this paper, we present a novel approach for using a multi-agent system for navigating one or multiple responders to one or multiple destinations in the presence of moving obstacles. Our navigation system supports information collection from hazard simulations, spatio-temporal data processing and analysis, connection with a geo-database, and route generation in dynamic environments affected by disasters. We design and develop a set of software geospatial agents that assist emergency actors in dealing with the spatio-temporal data required for emergency navigation, based on their roles in the disaster response. One of the key components of the system is the path planning module, which combines the modified A* algorithm, insertion heuristics, and auction algorithm to calculate obstacle-avoiding routes for multiple responders with multiple destinations. A spatial data model is designed to support the storage of information about the tasks and routes produced during the disaster response. Our system has been validated using four navigation cases. Some preliminary results are presented in this paper and show the potential of the system for solving more navigation cases.

1. Introduction

First responders play an important role in crisis management, saving people's lives during disasters. They are personnel from different agencies, e.g., fire brigade, police and medical care, and are responsible for a wide range of tasks, including searching for survivors, transporting relief goods, and evacuating and transferring wounded people. Most of these emergency tasks require fast and safe navigation as well as the coordination of the response teams. As the economic and human losses due to natural, man-made and human invoked disasters are increasing (Munich, 2015), much more research efforts have been devoted to the issues in disaster management and a special attention has been paid to the navigation for first responders in disaster response.

One of the challenging issues is that natural or man-made disasters can create all sorts of moving obstacles that affect the road network, making some roads dangerous or impossible to traverse. Using traditional routing algorithms, Mioc et al. (2008) and Chitumalla et al. (2008) develop applications that use the forecast information of hazards in the near future in routing and providing navigation services taking blocked areas or streets into account. Nevertheless, they lack a consideration of the dynamics of the environment affected by the moving obstacles, which may make the planned path longer than the shortest one. In some situations, the responders can pass through the threatened roads before they are affected, instead of just avoiding them. Because the status of the road network affected by moving obstacles changes over time, the temporal aspect should also be considered in the routing process. Similar research in the field of robotics on navigation in the presence of moving obstacles has been considerable (Phillips & Likhachev, 2011; Li et al., 2009; Narayanan et al., 2012), which could be beneficial to the research on navigation for first responders in some aspects. Another important issue is that the collaborative activities among emergency agencies require the coordination of their routes and destinations. Because the first responders often work in groups and perform tasks together, they need not only to obtain individual routes but also to take into account other response units in the routing process. For example, in the case of emergency medical service, ambulances are distributed to different destinations to pick up and deliver patients according to factors such as the situation of the patients, the deployment of the paramedics, and the availability of medical supplies in hospitals. Although numerous techniques have been proposed in logistical planning and robotics to achieve the efficient allocation of vehicles (Dias et al., 2006), they do not have any effective mechanisms to deal with moving obstacles, and cannot be applied to

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the environment affected by disasters. Therefore, there is a great need for an emergency navigation system that is capable of quickly and safely navigating multiple responders to multiple destinations, avoiding moving obstacles.

In this study, we apply the agent technology to address navigation problems with moving obstacles. The method of agent technology was introduced by Wooldridge & Jennings (1995) and represents a diagram for the development of software entities that automates specific computer-based tasks. Agent technology has a set of features, including supporting distributed control, allowing for flexibility and adaptability, etc., which make it suitable for development of the system for navigation in the presence of moving obstacles (Wang & Zlatanova, 2013b). The agent technology has been applied to very varied fields, for example, crisis management (Schoenharl & Madey, 2011) and supply chains (Vok et al., 2010; Zeddini et al., 2008). Recently, there has been increasing interest in applying agent technology to GIScience (Sengupta & Sieber, 2007; Crooks & Wise, 2013). Most work in this direction has been devoted to the use of multi-agent systems to simulate and study the behavior and interactions of humans in environments (Chen & Zhan, 2008; Torrens et al., 2012; Bonabeau, 2002). On the other hand, more and more researchers have applied the agent technology to the development of software spatial agents, which assist users in the analysis and evaluation of spatial problems (Genc et al., 2013; Nourjou et al., 2013). However, these agents are usually developed to address a particular set of geospatial issues, which limits their application to other problems, such as emergency navigation. Because the path planning in the presence of moving obstacles is characterized by its reliance on the large amounts of dynamic spatial data produced in disasters (Visser, 2009; Mioc et al., 2008; Wang & Zlatanova, 2013a), special types of agents, combined with GIS functionalities, are needed to quickly process and analyze the spatio-temporal data needed for navigation during the disaster response.

In this paper, we focus on addressing a subset of navigation cases presented in Wang & Zlatanova (2013c), and propose an integrated navigation system for first responders in the presence of moving obstacles, based on a multi-agent system. Our system extends the framework described in Wang & Zlatanova (2013b), and introduces a set of modules that are comprised of software agents for its spatial data processing and analysis. Such an approach can allow the system to be easily adjusted and applied to various navigation cases. We use hazard models to provide the predicted information about the obstacles, and select a geo-database in which to store the data needed for emergency navigation. A new one-to-one path planning algorithm is adapted from Wang & Zlatanova (2013a), and is combined with other path planning algorithms to calculate obstacle-avoiding routes for responders with one or multiple destinations. The remainder of the paper is organized as follows: Section 2 presents the navigation cases we aim to address in this paper, and describes the conceptual framework designed for navigation in the presence of moving obstacles. In Section 3, we illustrate the architecture of the proposed multi-agent based navigation system, which contains different types of agents and geo-database. In Section 4, we provide the algorithms used for the different types of path planning problems. Section 5 describes the implementation of our proposed system, and presents some of the results of applying this system to four navigation cases. Finally, we discuss some aspects of the system and conclude with an outline of future research in Section 6.

2. Conceptual analysis and design

This section first provides a taxonomy of navigation in the presence of obstacles. In this taxonomy, we examine and analyze different navigation cases, and place our studies in this paper in the broader context of navigation for first responders. After that, we present our approach, which supports routing in these navigation cases, and describe the general architecture of our navigation system.

2.1. Conceptual analysis of navigation cases with obstacles

This research is motivated by navigation problems that arise during disaster response. To help describe the similarities and differences between the navigation cases during disasters, we have constructed a taxonomy in the domain of navigation in the presence of obstacles (Wang & Zlatanova, 2013c), offering some broad keywords and phrases that characterize these cases. In this taxonomy, we identify the following set of criteria and their typical values. We refer to each combination of different values of each criterion as a case, and represent it in the form of a quadruple:

$$< X_1, X_2, X_3, X_4 >$$

where

(1)X_1 is the number of responders (one or many)
(2)X_2 is the number of destinations (one or many)
(3)X_3 is the type of the destinations (static or dynamic)
(4)X_4 is the type of the obstacles (static or moving).

For example, the case denoted by $<o, M, D, m>$ means one moving object has to be routed to many dynamic destinations, avoiding many moving obstacles.

In this taxonomy, there are, in all, sixteen navigation cases. We investigated previous work on these navigation cases in the fields of emergency management and robotics. According to our investigation, only a few studies have paid attention to navigation in the presence of moving obstacles in real road networks (Wang & Zlatanova, 2013a; Visser, 2009). To start with, in this paper we mainly focus on the

Table 1
The considered four navigation cases.

Navigation case	Description
• $< o, O, S, m >$ One moving object has to be routed to one static destination, avoiding many moving obstacles.	This situation may occur when a relief vehicle has to be navigated through an area affected by toxic plumes. In the case of plumes, the affected roads could be temporarily closed and be available again in the near future. Therefore, a waiting option can be employed in the routing to minimize the total travel time, in the meantime avoiding the moving obstacles.
• $< m, O, S, m >$ Many moving objects have to be routed to one static destination, avoiding many moving obstacles.	A classical example of this situation is navigating a certain number of fire trucks to a fire point. This problem can be split into subproblems by navigating moving objects separately, which can be addressed by the approaches proposed for $< o, O, S, m >$.
• $< o, M, S, m >$ One moving object has to be routed to many static destinations, avoiding many moving obstacles.	One typical example is guiding a fire brigade to several emergency locations in an area affected by floods to rescue victims, clean roads, and help pump water out of the flooded house. The navigation system must be able to plan a trip connecting these locations in a dynamic environment, which can be addressed as a dynamic version of the traveling salesman problem (TSP).
• $< m, M, S, m >$ Many moving objects have to be routed to many static destinations, avoiding many moving obstacles.	This may happen when some rescue vehicles are sent to many places to deliver goods and services during a flood event. The navigation problem in this case can be formulated as a multiple traveling salesmen problem (MTSP), and requires the distribution of the tasks among the responders while taking into account the moving obstacles.