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A data model for route planning in the case of forest fires

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The ability to guide relief vehicles to safety and quickly pass through environments affected by fires is critical in fighting forest fires. In this paper, we focus on route determination in the case of forest fires, and propose a data model that supports finding paths among moving obstacles. This data model captures both static information, such as the type of the response team, the topology of the road network, and dynamic information, such as sensor information, changing availabilities of roads during disasters, and the position of the vehicle. We use a fire simulation model to calculate the fire evolution. The spread of the fire is represented as movements of obstacles that block the responders' path in the road network. To calculate safe and optimal routes avoiding obstacles, the A* algorithm is extended to consider the predicted availabilities of roads. We prove the optimality of the path calculated by our algorithm and then evaluate it in simulated scenarios. The results show that our model and algorithm are effective in planning routes that avoid one or more fire-affected areas and that the outlook for further investigation is promising.

1. Introduction

Natural fires have caused enormous socioeconomic losses and created many victims in the past few years. Recently, there has been growing interest in understanding and mitigating the effects of these disastrous events. In fighting forest fires, a wide range of response activities and emergency operations are involved, such as transporting injured persons, distributing supplies, and evacuating citizens, all of which require navigation aids. Because the radiant heat released during burning can be considered obstacles that might make some roads unsafe and temporarily inaccessible (Taylor and Freeman, 2010), emergency managers need a path planner that is capable of finding a safe and optimal route that avoids fire-affected areas.

Navigation has been thoroughly studied from varied theoretical perspectives and across multiple disciplines, such as robotics, geomatics and applied mathematics (Chabini and Lan, 2002; Ge and Cui, 2002; Huang et al., 2007; Delling et al., 2009). Nevertheless, very few research efforts have been devoted specifically to emergency navigation problems in the context of moving obstacles that dynamically affect the road network (Wang and Zlatanova, 2013b). Although some studies have some relevance for route planning in the case of disaster events (Mioc et al., 2008; Liu et al., 2006), the issues that arise in the path planning during disasters have not yet been fully addressed. On one hand, the existing emergency support systems (Parker et al., 2008; Johnson, 2008) are capable of finding the shortest route to a certain location, taking the damages to the infrastructure into account, but do not consider the dynamics of disasters, particularly the predicted information on their developments, which limits their practical applications in disaster response. Some studies of emergency navigation used crowdsourced data regarding the state of the road to calculate the shortest path (Nedkov and Zlatanova, 2011; Neis et al., 2010). However, they can only cope with static obstacles, and do not offer the routing functionality required to avoid moving obstacles. On the other hand, most research on dynamic obstacles has been centered on robotics (Li et al., 2009; Masehian and Katebi, 2007; Gonzalez et al., 2012). The results from these studies could benefit the navigation of first responders in certain aspects. Nevertheless, the focus of their research is mainly on planning obstacle-avoiding paths in a given free space, without the constraints of a transportation network.

One of the most critical aspects in emergency navigation is information, most of which falls into two categories, static and dynamic. Static information is relevant to topographic and territorial data (e.g., land use, road network, buildings, and locations of fire hydrants). Most of the static data can be obtained through municipality offices and the emergency response (ER) sectors, as well as public resources, such as the location of fire hydrants on www.openfiremap.organd general maps from OpenStreetMap (www.openstreetmap.org). Dynamic information is more related to the incident description and its impacts, damages, sensor

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measurements, etc., and has a highly temporal aspect, i.e., it changes rapidly over time. This information consists of historic information, about what has happened since the disaster occurred, and predicted information, about what may happen. Examples of historical information are the type, scale, and affected area of an incident, the number of injured and missing people, etc. This information is needed to help emergency managers identify dangerous areas that should be avoided. Examples of predicted information are the likelihood of floods in a given 2.5-dimensional terrain, areas threatened by gas plumes, the forecasted wildfire front, etc. Such information is also needed to assist planners in adjusting original route plans in advance of developing disasters.

For the above reasons, a hazard simulation model that is capable of providing reliable predicted information about disaster changes, is a valuable framework that underlies the solutions for many problems that arise in the context of advance rescue planning. Many hazard models have emerged to encourage and facilitate emergency operations in the past few years (Hu, 2011; Moreno et al., 2012, 2011; Zelle et al., 2013; Lu et al., 2008). For example, Zelle et al. (2013) present an integrated system for smoke plume and gas cloud forecasts, combining a weather model, a smoke plume model, and a crisis management system. Moreno et al. (2011) present a real-time fire simulation algorithm that can be integrated into interactive virtual simulations where fire fighters and managers can train their skills. These models make it possible for emergency workers to assess the potential impact of a hazard, identify dangerous areas that should be evacuated, and make effective plans to curb damages and protect lives.

In our research, a geo-Database Management System (geo-DBMS) is selected to manage hazard simulation results and dynamic information of geographic objects. The Geo-DBMS provides efficient management of large spatial data sets (often encountered in large scale events). In addition, it has mechanisms that enable fast update and access to geographic information, and functionality for data analysis. The geometric model, which has been used and implemented in major geo-DBMSs (e.g., Oracle Spatial, PostGIS) (Meijers et al., 2005), makes the systems capable of handling all types of spatial data related to disaster management. Some data models have been developed in geo-DBMSs for emergency response (Dilo and Zlatanova, 2011; Kwan and Lee, 2005; Zlatanova and Baharin, 2008). However, they are not capable of dealing with predicted information from hazard simulation models and cannot support routing among moving obstacles. Many researchers have been working on managing moving objects and numerous data management techniques have been developed to facilitate the collection, organization, and storage of dynamic data of moving objects (Wolfson et al., 1998; Meratnia, 2005; Güting et al., 2006). These studies provide a rich set of solutions for managing the dynamic information produced during disasters, such as the locations of the rescue unit, plume movement, and changes in the water level.

In this paper, we focus on the routing process in a real road network in the case of forest fires. We use a fire simulation model to generate datasets about the spread of the fire, and obtain information about its damage to the infrastructure through spatial data analysis. A spatio-temporal data model is proposed to structure dynamic information of transportation conditions affected by fires in the database. Using this information, we apply a modified shortest path algorithm to calculate optimal paths avoiding fire-affected areas for first responders. Such an approach is not limited to route planning during forest fires, but also can be extended to assist navigation among moving obstacles brought about by other types of disasters.

The organization of the paper is as follows. In Section 2, we describe our system architecture for emergency navigation. Section 3 presents both conceptual and logical spatio-temporal data models of the dynamic information for routing to avoid obstacles. Section 4 illustrates the network analysis application, including the extended A* algorithm. Section 5 gives definitions of route safety for evaluation of the calculated routes. Section 6 describes the detailed implementation of our navigation system. In Section 7, we test the model and the algorithm in different scenarios, and detail our results. We draw some conclusions in Section 8 and end this paper with proposed future work in Section 9.

2. System architecture

To assist fire fighting in forest areas, a system architecture for routing avoiding fire-affected areas is designed. The framework of the proposed system is depicted in Fig. 1 and is composed of the following components: data collection, data management, fire simulation model, agent-based simulation model, and visualization of simulation results. When a fire incident occurs, several measurement teams are formed and sent into the field to perform measurements. Real-time sensor information (e.g., wind speed and wind direction) is collected from the field via a communication network, and is incorporated into the fire simulation model to achieve more accurate predictions of fire spread. The fire model (Moreno et al., 2011) produces dynamic data of spatial units about the fire state, from which the shape and direction of movement of fires are derived. This dynamic information, together with the geo-information of the network and the information regarding response units (routes, starting point, end point, status, etc.) is consistently recorded and structured in a geo-DBMS based on the data model designed for emergency response (Dilo and Zlatanova, 2011). We use an agent-based simulator with GIS functionalities to predict the availabilities of roads in a certain area at a certain time, and to display the movement of both the fire and the responders. The fire simulation results are represented as one or more moving polygons crossing a certain road network. The first responder is modeled as an agent characterized by a set of attributes (e.g., speed, type of vehicle) and performs certain actions (e.g., moving, waiting). Using predicted information about the state of roads, the path planner, within the agent, applies the shortest path algorithm to calculate the safest and fastest route for responders. The calculated results are visualized to users through a 2D view as well as a navigable 3D view to enhance human situational awareness (Schurr et al., 2005).

3. Data model design

A spatial temporal data model is needed to effectively organize all required information and knowledge in the geo-DBMS.

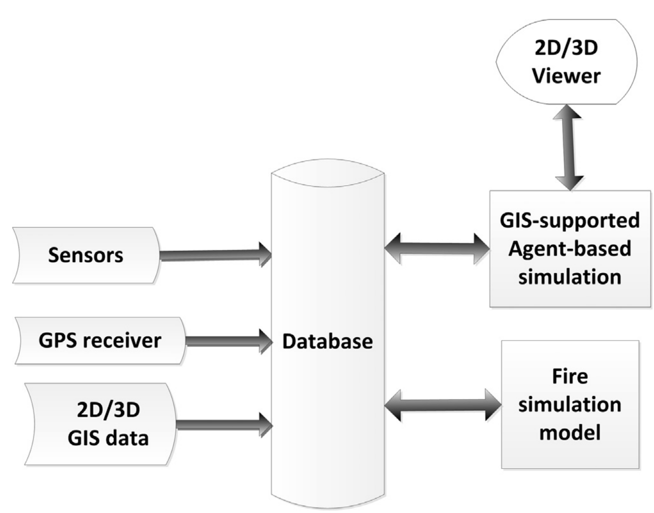

Fig. 1. The overview of the proposed system architecture.