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The application of geometric network models and building information models in geospatial environments for fire-fighting simulations

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ABSTRACT

This study was motivated by the need to develop a micro-geographic information system (GIS) to represent and analyze 3D spatial data for fire-fighting simulations. The proposed method involved exploration of a 3D geometric network model (GNM)-based, building information model (BIM)-supported framework for fire-fighting simulation. The operations of ladder trucks were simulated in a virtual 3D environment. Using the method described in this paper, the best position for the deployment of the ladder trucks can be determined even before the arrival of firefighters at the scene. A real fire-fighting drill was also conducted as part of this study. The proposed method can assist firefighters quickly locate their ladder trucks, thereby reducing response time after an incident.

1. Introduction

A public fire department provides vital assistance to victims of fire in protecting their lives and property (Deng, Hsieh, Yang, & Sheu, 2001). After a fire starts, it usually spreads rapidly, and often causes a great deal of damage in a very short period of time (Mattsson & Juås, 1997). Unfamiliarity with the interior of a building may affect a firefighter's ability to fight a fire. In a real emergency situation, the task of finding one's way into a building becomes a challenge, especially when there is little or no visibility due to smoke or power failure. High levels of mental and physical stress may add to the difficulty. Getting lost in a burning building can have fatal consequences to a firefighter if his oxygen supply runs out. On the scene, firefighters typically have no knowledge of the interior structure, hallways, exits, etc. of a building. Typically, the only information available to fire brigades is 2D floor maps. However, floor maps do not provide detailed semantic information. In addition, a real fire scene is actually a 3D environment that includes both the interior and exterior of a building. Important information, e.g., the size and type of doors and windows, the distance from the entrance to the incident site (which is needed for the deployment of fire hoses), rescue routes, which window is accessible to the fire truck, etc., is needed for successful fire-fighting operations at a fire scene. A potential source of 3D building data is a building information model (BIM). The most important characteristics of BIMs are 3D information and semantic information. In this study, BIMs were implemented to facilitate emergency response operations in a fire situation.

At many fire scenes, especially in urban areas, fire departments have to deploy ladder trucks (with aerial equipment) for rescues, ventilation, access to upper floors and fire suppression. The greatest challenge for ladder trucks is overcoming their aerial limitations. Firefighters can add length to hoses to reach the fire, but they cannot stretch the ladders to reach the building. The operating procedures of a ladder truck include: (1) positioning truck, (2) outrigger leveling, (3) operating ladder, (4) fire-fighting operations, and vice versa. Once the parking brake is set and the outriggers are dropped, the ladder truck is in position for the remainder of the job. Repositioning will require a significant investment of effort and time. Therefore, firefighters should make all efforts to get it right on the first try. The first-in members of the crew need to evaluate the fire scene for optimal ladder truck placement, placing their trucks close enough to the building so that firefighters can use the aerial position to fight the fire. However, this can become a challenge because of competition for space at the scene (Bernocco & Andrus, 2003). For example, the placement of ladder trucks may be complicated by the positions of other fire trucks, ambulances, police cars and hose lines. Virtual 3D city models can be used in different application areas such as disaster management (Over, Schilling, Neubauer, & Zipf, 2010). Virtual reality, which involves modeling, simulation, and visualization, is a powerful technology for users to interface and interact with virtual environments. Virtual

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reality has already had a significant impact on emergency management, including advanced data visualization systems within geographic information systems (GIS). Many advanced decision support systems for emergency management rely on GIS technology and virtual instrumentations (Beroggi, Waisel, & Wallace, 1995). In addition, performing a fire drill in modern cities under realistic fire conditions can be difficult. A virtual environment could provide a variety of fire-fighting scenarios for instruction and evaluation in a more realistic manner than verbal or written material and with less risk and expense than fighting real fires.

This study was motivated by the need to develop a micro-GIS to represent and analyze 3D spatial data for fire-fighting simulations. The main objective was to simulate the operation of ladder trucks in a virtual 3D environment. Before firefighters' arrival at the scene, the best position for the ladder trucks can be determined, as well as how other vehicles should be moved to other positions to avoid blocking the ladder trucks, which is a priority. This manual operation can be performed with a graphical user interface (GUI) of the system. The area of reach of the ladder trucks can therefore by maximized and opportunities for access, rescue and elevated master streams can be identified. The rest of this paper is structured as follows. Section 2 reviews related works and Section 3 describes the system architecture. Section 4 outlines fire scenario case studies. The simulated drill is described in Section 5. Conclusions and plans for future research in Section 6.

2. Related works

GIS have been used to optimally site fire stations to minimize the response time for dispatching a crew to a fire scene (Liu, Huang, & Chandramouli, 2006). However, in the event of a fire, the complex internal structures of buildings and traffic congestion can also make pedestrian evacuation and rescue operations difficult. Emergency response to incidents requires optimal routes not only on the streets but also within buildings (Kwan & Lee, 2005). GIS were originally developed by representing 3D real-world entities as 2D objects, i.e., points, lines and polygons, in either vector or raster data structures. However, these 2D models cannot fully represent the real 3D world, especially when we are interested in a detailed description of the internal structure of a 3D spatial entity (Shi, Yang, & Li, 2003). Several 3D GIS methods have been developed in the past decade. However, recently developed 3D GIS data models have limitations in terms of geometric and topological representations of the complex internal structure of buildings at the 3D subunit level (i.e., not many previous studies are concerned with visualizing interior structures of buildings).

Lee and Kwan (2005) developed a new way to represent the topological relationships among 3D geographical features, namely, the combinatorial data model (CDM). The CDM for a node-relation structure (NRS) can be derived through Poincaré duality, abstracted from the topological relationships among a set of 3D objects, transforming "3D to 2D relationships" in primal space to "0D to 1D relationships" in dual space. Adjacency relationships among objects in 3D space are represented by a dual graph, $G = (V(G), E(G))$. For connectivity relationships in the NRS, the graph $H = (V(H), E(H))$ is a subset of the graph $G = (V(G), E(G))$. The CDM is a pure graph that represents the adjacency, connectivity and hierarchical relationships among the internal units (e.g., rooms and corridors) of a building. It does not represent the geometric properties (e.g., size or distance) of these units. To perform 3D analysis, such as shortest path analysis, the CDM needs to be transformed into another data model, called the geometric network model (GNM). Fig. 1 shows an NRS for representing topological relationships among 3D units. Their GNM with the shortest path algorithm in emergency response can reduce the response time required to reach a disaster site inside a multistory building. However, their GNM does not account for temporal variations (e.g., movement of smoke at different times during a building fire). Wu and Chen (2012) proposed a spatio-temporal analysis method for finding fire-fighting rescue routes that could quickly locate a destination and show the shortest safe path within a building. They used a GNM and the Dijkstra algorithm to consider smoke movement during different time of a building fire. Therefore, the route calculation can avoid routes through heavy smoke within buildings. In their future work, the GNM should be integrated with an outdoor GIS system. Thus, the proposed routes would not only for use within the buildings but also for street transportation. Thill, Dao, and Zhou (2011) developed a network-based 3DCityNet for urban analytical functionalities such as route planning, spatial accessibility assessment, and facility location planning. Their 3DCityNet offers significant analytical capabilities of built environments also in micro-scale spaces (i.e., their route planning enables users to query the least-effort route between any two points, whether these points are situated indoor or outdoor). However, future research on 3DCityNet is needed to develop enhanced visualization tools which provide greater interactivity (e.g., attribute queries by clicking on the screen). Isikdag, Underwood, and Aouad (2008) applied BIMs in geospatial environment in order to facilitate the data management in site selection and fire response. Their research demonstrated that BIMs can provide the required geometric and semantic information about buildings in support of site selection and fire response management process (i.e., BIMs can provide attribute queries about building elements). However, a real fire scene is a dynamic progress. Some variations may change during a building fire (e.g., movement of smoke, positions and operations of a ladder truck, etc.). Therefore, an interactive 3D environment is needed to simulate a fire scene.

In this study, we proposed a method involved exploration of an interactive 3D GNM-based, BIM information-supported framework for fire-fighting simulation, which could be notified as the scientific contribution of this research. This study provided useful decision support of fire-fighting operations such as route navigation for firefighters in a virtual 3D environment, demonstration of movement of smoke at different stages during a building fire, deployment of a virtual ladder truck in a fire scene, and attribute queries of building elements using BIMs, etc.

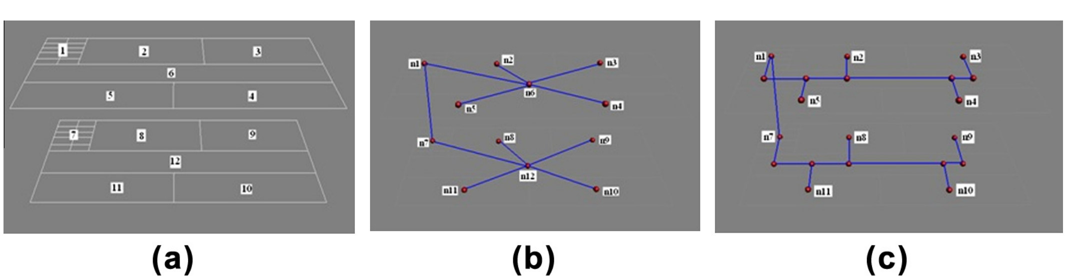

Fig. 1. An illustration of the node-relation structure: (a) 3D spatial units, (b) combinatorial data model, and (c) geometric network model.