Providing guidance for evacuation during emergency based on a real-time damage and vulnerability assessment of facilities

G. Guven[1], E. Ergen[2], M. A. Erberik[3], O. Kurc[4] and M. T. Birgönül[5]

[1] Doctoral Student, Civil Engineering Department, Istanbul Technical University, Istanbul, 34469, TURKEY; PH (90) 212 285 7399; email: gursans.guven@itu.edu.tr
[2] Assistant Professor, Civil Engineering Department, Istanbul Technical University, Istanbul, 34469, TURKEY; PH (90) 212 285 6912; email: esin.ergen@itu.edu.tr
[3] Associate Professor, Civil Engineering Department, Middle East Technical University, Ankara, TURKEY; PH (90) 312 210 2443; email: altug@metu.edu.tr
[4] Assistant Professor, Civil Engineering Department, Middle East Technical University, Ankara, TURKEY; PH (90) 312 210 2447; email: kurc@metu.edu.tr
[5] Professor, Civil Engineering Department, Middle East Technical University, Ankara, TURKEY; PH (90) 312 210 2427; email: birgonul@metu.edu.tr

ABSTRACT

Following a disaster or an emergency situation (e.g., earthquake,) in a facility, it is crucial for emergency response teams to rapidly access navigation information of the facility, its contents and the final status of the facility (e.g., damages and vulnerable locations). However, in the current practice, accessing these information items is time-consuming and the accessed information is incomplete, since there are multiple sources of information that are mostly disorganized. This study proposes a Building Information Model (BIM) based approach integrated with sensors to provide the damage and vulnerability information of the facility for efficient response and for safe evacuation of the facility. The proposed framework integrates navigation algorithms, a vulnerability assessment approach and the status information obtained from various sensors that are strategically deployed inside the facility. This framework will be used for guiding the occupants and rescue teams through safe locations in a facility during evacuation.

INTRODUCTION

When an emergency situation occurs in a facility or when a disaster (e.g., earthquake) strikes a facility, multiple parties including first responders, emergency response teams, and occupants require information about the building, such as its structure, damage condition, contents and vulnerable locations. Moreover, in many cases, disasters such as earthquakes trigger other hazardous situations in buildings (e.g., post-earthquake fires), and thus, responders and occupants need to deal with multi-hazard emergencies. Such conditions require first responders to perform rapid vulnerability assessment and evacuation in facilities. In the current practice, information about the damaged building, building content and occupancy condition is not completely available to response teams (Jones and Bukowski 2001, Evans et al. 2005, Son and Pena Mora 2006). The lack of such necessary information affect the efficiency of response operations, and this leads to increases in the number of casualties during emergency situations (Kwan and Lee 2005, Ergen and Seyis, 2008). Therefore, there is a need for an approach that enables rapid damage and vulnerability assessment in facilities, guides occupants during evacuation and directs emergency response teams to vulnerable locations.

This study proposes a framework that utilizes Building Information Model (BIM) integrated with sensors to provide the damage and vulnerability information of a facility that is under the threat of multi-hazard emergency situations. The main goal is to efficiently guide the occupants during the evacuation of the facility and assist emergency response teams in rescue operations. In the study, the native BIM file is transformed into Industry Foundation Classes (IFC) format, from which a graph network model (GNM) is obtained by defining graph network elements in IFC. The obtained model is then integrated with the results of the vulnerability assessment along with the status information obtained from different sensors that are deployed inside the facility. The navigation algorithms run on the resulting model, calculating the safest evacuation path based on the damage and vulnerability conditions. In this paper, the proposed system framework is provided and the research challenges are discussed.

BACKGROUND RESEARCH

Effective evacuation of damaged buildings following a disaster or an emergency situation is crucial for saving more lives. However, it is difficult to effectively evacuate buildings on time since buildings might have complex indoor environments. Moreover, a primary disaster (e.g., earthquake) might trigger secondary disasters (e.g., fires) which requires first responders to contend with multi-hazard situations, and makes it even harder to evacuate buildings efficiently. To address these issues, previous studies about emergency response focused on navigation. Some of these studies developed navigation systems that are integrated with BIM and/or two or three dimensional (i.e., 2D, 3D) Geographic Information System (GIS) since indoor navigation heavily relies on the accurate representation and storage of building information (Lee 2005; Kwan and Lee 2005; Qing et al. 2006; Lee 2007; Lee and Zlatanova 2008; Ivin et al. 2008; Park and Lee 2008). Recent studies revolves around indoor navigation, rather than outdoor navigation (Meijers et al. 2005; Pu and Zlatanova 2005; Kwan and Lee 2005; Qing et al. 2006; Yuan and Zizhang 2008). By using indoor navigation approaches, alternative evacuation paths are created following emergency (Lee 2007; Lee and Zlatanova 2008; Yuan and Zizhang 2008; Park and Lee 2008; Rueppel and Stuebbe 2008).

In addition to accurate and up-to-date geometry and semantics of buildings; Yuan and Zizhang (2008) highlighted the need for information about threats and building accessibility for a successful indoor navigation. In their study, information provided by BIM is integrated with 3D GIS for determining the evacuation paths during emergency response. Another study utilized 3D GIS to obtain information related to a building for generating graph networks to be used for navigation during emergency response (Lee 2007). Other similar studies used data in IFC format for computing accessible distances for handicapped people in wheelchairs based on a length-weighted graph structure and the objects needed for creating a graph network for indoor navigation (e.g., IfcSpace, IfcDoor) are determined (Lee et al. 2008; 2010).

The previous studies do not include the information about the overall status and condition of the building following a disaster or emergency in the navigation approaches. However, it is important to consider the damaged locations and parts of the building during evacuation for the safety of occupants and the responders. Therefore, the framework proposed in this study utilizes sensors to obtain the status information of the building and integrates this information with navigation algorithms to guide the occupants and the responders during evacuation.

Another important aspect during emergency response is to perform vulnerability assessment in the damaged building and to identify vulnerable locations and contents. There are a few studies that focus on building-scale vulnerability assessments (Leite et al. 2008; 2009; Leite and Akinci 2012). Leite and Akinci (2012) presented a formalized vulnerability representation schema that is aimed to support vulnerability assessment during building emergencies with a facility management point of view. For example, it identifies which critical contents in the facility (i.e., server computers) might be affected by an emergency that is triggered by a failure in a building system (i.e., power outage). It mainly focuses on building systems failures that might directly impact a facility and its critical contents Leite and Akinci (2012). However, the study explained in this paper focuses on building emergencies that are caused by disasters (e.g., earthquakes) with an emergency management viewpoint and building system failures are not in the scope of this study. In this study, hazardous contents in buildings, their potential effects on human lives and the way that they can interfere with the evacuation process are considered.

OVERVIEW OF THE PROPOSED FRAMEWORK

In this study, vulnerability assessment is defined as the process of identifying the location of hazardous materials and determining the potential threats that are susceptible to these materials. Threats are the building contents that can have harmful effects in case of a disaster and/or can develop secondary disasters, such as explosion or fire. Vulnerable locations that contain hazardous materials and threat bearing contents have the possibility to cause injuries and mortality. The vulnerable locations that are in close proximity of occupants should be avoided during emergencies.

To describe how the proposed system works, and to explain its functions and scope in detail; a system framework is developed (Fig. 1). The proposed framework mainly composes of three steps: (1) placing nodes and edges into the IFC-based building model, (2) creating a deformed GNM of the building which includes up-to-date damage condition and vulnerability assessment results, and (3) providing shortest paths to the users. The graph network elements (i.e., nodes and edges) are created in an IFC-based building information model as a first step towards identifying evacuation paths. The different types of sensors that are deployed inside the building will provide information about the status of the building (e.g., blockage and damage status). The status information obtained from sensors and the vulnerability analysis results will be transferred to the graph network that is driven from the IFC-based building model. The resulting GNM that includes the vulnerable and damaged locations inside the building is the deformed GNM of the building. The last step is to compute the shortest evacuation paths based on the up-to-date building information and the results of the vulnerability assessment. Following paragraphs provide the details for each step.

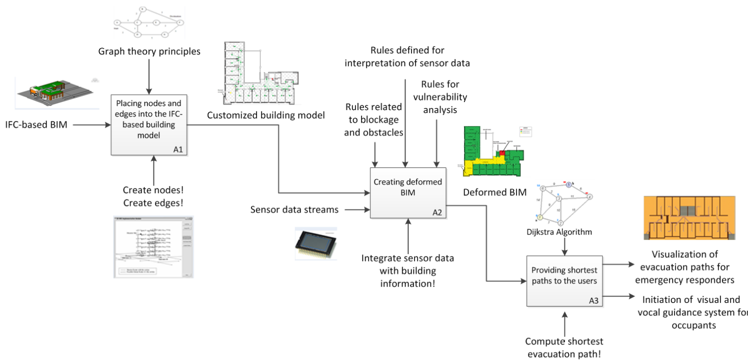

Figure 1. Proposed system framework

Step 1: Placing nodes and edges into the IFC-based building information model. In this step, the graph network will be developed using the information related to each storey in a building and other required information contained in BIM. This will be the basis for the shortest path algorithms (SPAs) which will compute the shortest paths according to the accessibility of routes inside the building.

IFC-based BIM: The proposed framework integrates the graph network driven from BIM, along with the SPA and the results of vulnerability analysis. All the information that is required to generate graph networks and to compute shortest paths (i.e., building geometry, plans and elements, storeys and spaces inside the building and their relations) will be obtained from the building information model. The building model will be created using a BIM tool (e.g., Autodesk Revit) and it will be exported to IFC format instead of working with the native format to enable interoperability. Also, IFC provides the opportunity to extend the standard to include the classes needed for creating graph networks (i.e., nodes and edges) which are not currently defined in IFC, by using programming languages (e.g., Java).

Graph theory principles: In mathematical definition, a graphic (G) is a set consisting of two finite sets called node (N) and edge (E), (i.e., G = (N, E)). While IFC standard provides information about buildings; graph network elements, nodes and edges, are not currently defined in IFC. Thus, the IFC standard needs to be extended to define the required objects, along with the attributes, methods and the relationship in between them, in accordance with the graph theory principles.

Creating nodes and edges: Graph theory elements are created by extending IFC based on the graph theory rules and principles, and the customized GNM is developed.

Customized graph network model: Customized GNM is obtained as the nodes and edges are placed into the IFC-based building model; and ready to be used as an input for the next step.

Step 2: Creating deformed graph network model. The information related to the status of the building and the accessibility of nodes and edges as well as the vulnerability information is used to determine: (1) the damage that is caused by the disaster, (2) the secondary hazards that are triggered by the disaster, and (3) the related risks. The data obtained from sensors (i.e., damage/blockage information) and the vulnerability assessment results are stored in the deformed GNM, which will be used as an input for the third and last step for computing the shortest paths.

Customized graph network model and sensor data streams: The customized GNM will be used to examine the accessibility of nodes and edges, while the sensor data will provide the status information regarding the condition of the building (i.e., damaged/blocked locations) following a disaster. The Cameras and different types of sensors (e.g., gyroscope, ultrasonic distance sensor) will be deployed on strategic locations to provide critical information on whether some building elements (e.g., columns, walls) are damaged (e.g., collapsed) or not.

Rules related to damage and blockage and rules for vulnerability analysis: The information retrieved from the sensors will be used to determine the accessibility of nodes and edges, and to understand the level of damage inside a building. There is a need for establishing some rules for combining and interpreting the information received from different types of sensors. The reason is that more than one type of sensor might be monitoring the same building element. In such case, these rules will be used to interpret the condition by considering the threshold values of each sensor, and the decision will be made based on whether the node or the building element related to the sensor is blocked/damaged or not.

Vulnerability assessment will be performed to evaluate the risks that are associated with the vulnerable building contents and the threats (e.g., fire) that a disaster (e.g., earthquake) can induce. The types of vulnerable contents that are present in the building and their locations are entered in BIM during the design phase. By using this predefined information, a vulnerability algorithm (i.e., vulnerability risk ranking) will prioritize all possible threats in accordance with the related risks, which may occur due to the vulnerabilities in the building. According to the results of the vulnerability assessment, vulnerable locations will be avoided in the shortest evacuation path calculation as much as possible. When an evacuation path must pass through one or more vulnerable location/s, this ranking approach will be used to choose in between the two vulnerabilities to create alternative evacuation paths.

Integration of sensor data with building information: The sensor data is integrated with the customized GNM that constitutes of nodes and edges. By the interpretation of the data obtained from sensors according to the predefined damage/blockage rules; the system decides whether a node is accessible or not (i.e., should be included in the shortest path computation or not).

Deformed graph network model: The damaged/blocked nodes of the customized GNM are determined by interpreting the data obtained from the sensors and the nodes to be added to the shortest path calculation are identified. Similarly, the risks associated with the vulnerabilities inside the building are determined with the vulnerability risk ranking approach. The resulting model reflects the condition of the building after the disaster, according to the vulnerability assessment and the damage occurred in the building. This is the deformed GNM that will be the input for the next step that calculates the shortest evacuation paths.

Step 3: Computing and providing shortest paths to the user. Shortest path computation will be performed by running SPAs in deformed GNM. For every node inside the building, shortest safe evacuation paths will be calculated and provided to the users as a means of vocal and/or visual guidance. Also, the paths that are computed for the occupants will be presented to the emergency response teams (e.g., via hand-held computers) to help them in performing effective search and rescue.
Deformed graph network model: The aim is to use the information stored in the deformed GNM as a basis for setting up the SPA and to compute the shortest evacuation paths that will help evacuate the occupants to safe places.
Dijkstra Algorithm: Dijkstra, which is a commonly used algorithm in computing the shortest path between two nodes (Ivin et al. 2008), will be used for shortest evacuation path calculations.
Computation of the shortest evacuation paths: In the final step, the shortest evacuation paths are calculated based on the vulnerability assessment results, and the damage/blockage condition of the building obtained from the deformed GNM.
Initiation of visual and vocal guidance system for occupants and the visualization of evacuation paths for emergency responders: After the shortest and safest evacuation paths are computed, the occupants will be guided in accordance with the computation results. Also, the emergency responders will be informed about the status of the building, the vulnerabilities and possible threats, and the evacuation paths that are provided to the occupants.

DISCUSSION

It is envisioned to use different types of sensors that are deployed in the building to obtain status information after a disaster. This limits the utilization of the proposed framework to the buildings with light to moderate damage only, since in heavily damaged buildings the sensors will become inoperative. Also, it is a challenging task (1) to work with different types of sensors and combine data retrieved in different formats and (2) to integrate the results with the IFC-based building model. For instance, the cameras will interpret visual information, as if a space is damaged/blocked or not. Similarly, the cable sensor will only give Boolean results such as a wall is damaged (i.e., 0) or not (i.e., 1); but it will not provide any specific information (e.g., to which side it has collapsed and how). On the other hand, the gyroscope gives the results in terms of angular velocity. Thus, to interpret the raw data obtained from sensors in different formats, some experiments should be performed with the sensors to determine their threshold values. Consequently, when a value exceeds the threshold, it will mean that the building element is damaged, otherwise not damaged. Also, further experiments should be carried out for the cases where some of the sensors are damaged while others are functioning properly. This will help understanding if the system still performs well when less number of sensors are available.
Moreover, there is a need to establish some rules regarding the situations when a building element is being monitored by more than one sensor, since different sensors might give contradictive results for the same element. To determine the reliability of each type of sensor, a number of experiments should be carried out to evaluate the success rate of each sensor in assessing a condition correctly.
Another challenge is to efficiently guide the occupants in accordance with the

shortest path computation results. This can be performed visually and/or vocally. Feasibility of different approaches should be evaluated. Also, a robust approach is needed to inform the responders of the paths to which occupants are directed and the conditions of the building.

CONCLUSIONS

This paper gives an overview of a framework that composes of IFC-based BIM integrated with sensors and vulnerability information for assisting responders and occupants following a disaster. The main objective of this study is to perform indoor navigation based on the final conditions of facilities determined through the assessment of the facility in terms of damage and vulnerability aspects after a disaster. Further research on the performance of sensors is planned as future work, such as conducting experiments for examining individual performance of sensors in determining building element conditions and for combining the data collected by multiple sensors,.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support provided by the Scientific and Technological Research Council of Turkey (TUBITAK), Grant No. 109M263.

REFERENCES

Ergen E., Seyis S. (2008). "Utilizing Advanced Storage Technologies for Providing Local Information to Rescue Teams Following an Earthquake." 5th Int. Conference on Innovation in Architecture, Engineering, Antalya, Turkey.

Evans, D. D. (2003). “First responders problems and solutions: tactical information.” Technology in Society, 25(4), 523–528.

Ivin, A.M., Alias, A.R. and Coors, V. (2008). “Implementing 3D Network Analysis in 3D-GIS”, Int. Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 37(B2), Beijing.

Jones, W.W., and Bukowski, R.W. (2001). “Critical information for first responders, whenever and wherever it is needed.” Interflam '2001, Sept. 17-19, Edinburgh, Scotland, 1073-1082.

Kwan, M. P. and Lee, J. (2005). “Emergency Response after 9/11: the potential of real-time 3D GIS for quick emergency response in micro-spatial environments”, Computers, Environments and Urban Systems, 93-113.

Lee, J. (2005). “3D GIS in Support of Disaster Management in Urban Areas”, http://www.directionsmag.com/article.php?article_id=2049> (Dec. 12, 2011).

Lee, J. (2007). “A Three-dimensional Navigable Data Model to Support Emergency Response in Microspatial Built-environments”, Annals of the Association of American Geographers, 97(3), 512-529.

Lee, J. and Zlatanova, S. (2008). “A 3D Data Model and Topological Analyses for Emergency Response in Urban Areas”, Geospatial Information Technology for Emergency Response, Taylor & Francis, UK, 143-168.

Lee, J.K., Eastman, C. M., Lee, J., Jeong, Y. and Kannala, M. (2008). “Accessible Distance Meausrement Using GT Metric Graph”, CIB W084, Georgia Institute of Technology, May 15-16, Atlanta, GA, USA.

Lee, J.K., Eastman, C.M., Lee, J., Kannala, M. and Jeong, Y. (2010). “Computing Walking Distance Within Buildings Using the Universal Circulation Network”, Env. and Plan. B: Planning and Design, 37(4), 628-645.

Leite, F., Akinci, B., Akin, O. and Garrett, J. (2008). "Supporting the Decision-making Process of First Responders in Building Emergencies: the Need for a Vulnerability Representation", ICE08, Plymouth, UK.

Leite, F., Akinci, B.; Garrett, J. and Akin, O. (2009). "Representation of Facility Contents and Threats for Supporting Identification of Vulnerabilities in Building Emergencies", ASCE Comput. Civil Eng., Austin, TX, 582-592.

Leite, F. and Akinci, B. (2012). "A Formalized Representation for Supporting Automated Identification of Critical Assets in Facilities during Emergencies Triggered by Failures in Building Systems", J. Computing in Civil Eng., doi:10.1061/(ASCE)CP.1943-5487.0000171.

Meijers, M., Zlatanova, S. and Pfeifer, N. (2005). “3D Geo-Information Indoors: Structuring for Evacuation”, Next Generation 3D City Models, Bonn, Germany, 11-16.

Park, L. and Lee, J. (2008). “Defining 3D Spatial Neighborhoods for Topological Analyses Using a 3D Network-based Topological Data Model CA-based Evacuation Simulation”, Int. Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 37, Part B2, 305-310.

Pu, S. and Zlatanova, S. (2005). “Evacuation Route Calculation of Inner Buildings”, Geo-Information for Disaster Management, 1143-1161, Springer Verlag, Heidelberg.

Rueppel, U. and Stuebbe, K. (2008). “BIM-Based Indoor-Emergency-Navigation-System for Complex Buildings” Tsinghua Science Technology, 13, 362-367.

Qing, Z., Yuan, L. and Khoon, T.Y. (2006). “3D Dynamic Emergency Routing”, GIM-International, 20(6).

Son, J. and Pena-Mora, F. (2006). “Improvement of collaboration among first responders including civil engineers during disaster response in urban areas”, 11th ICCBE, June 14-16, Montreal, Canada.

Yuan L. and Zizhang H. (2008). “3D Indoor Navigation: a Framework of Combining BIM with 3D GIS”, 44th ISOCARP Congress.