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Requirements of Indoor Navigation During Emergency Response and Disaster Management

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Abstract

The safety of occupants in facilities is threatened by several types of disasters (e.g., earthquakes), and various emergency situations following those disasters, such as post-earthquake fires. It is crucial to successfully evacuate buildings following disasters and during emergency situations since it has the potential to decrease the number of injuries and mortality. However, complexity of some indoor environments (e.g., large public buildings) makes it difficult to effectively evacuate buildings. Thus, there is a need for a navigation approach for the occupants and the first responders following an emergency situation or a disaster. This research study focuses on indoor navigation in buildings that has complex indoor environment and addresses the issues observed during building evacuation. The main purpose of the study is to identify the requirements for providing guidance to the first responders in a building during emergency response and to the occupants for evacuating a building. To elicit the requirements for navigation, multiple use cases related to disasters or emergency situations in complex buildings are developed. These use cases are analyzed to identify common navigation needs. The results of the study can be used for developing an automated building navigation system for the occupants and response teams.

1 Introduction

Disasters (e.g., earthquakes) threaten the safety of occupants. It is also common that earthquakes can trigger other emergency situations, such as post-earthquake fires where the number of injuries and mortality caused by such fires may be substantially larger than the earthquake [1]. Therefore, following a disaster/emergency situation, it is crucial to effectively evacuate a building by considering the current damage and the potential emergency situations that can be triggered. This is especially difficult for buildings with complex indoor environments (e.g., large public buildings). Thus, there is a need for an effective navigation approach in such buildings for the occupants and the first responders following a disaster/emergency situation.

Previous studies about emergency navigation focused on outdoor environments. Recently, after World Trade Center and London subway disasters, studies revolved around navigation in indoor environments, and majority of these studies utilized integrated navigation systems using 2D/3D GIS or similar 3D models [2-7]. Some studies combined navigation systems with Building Information Models (BIM) [2]. In other studies, some indoor emergency navigation requirements were determined [4]. However, requirements of an indoor emergency navigation system were not examined thoroughly.

This research study focuses on indoor navigation in buildings that have complex indoor environments. It addresses the issues observed during building evacuation to identify the requirements for providing guidance to the first responders during emergency response and to the occupants during evacuation. Multiple use cases related to disasters and emergency management in complex buildings are developed for identifying the requirements. The results can be used for developing an automated building navigation system for the occupants and response teams.

2 Literature review

There are several studies about indoor navigation during emergency response and disaster management in the literature. Yuan and Zizhang [2] suggested a framework combining BIM with 3D GIS for indoor emergency navigation. Semantic information about the building is derived from the BIM and a semantic model for graph network generation is integrated with Straight Medial Axis Algorithm [2]. This tool enabled indoor navigation during emergencies. Similarly, Meijers *et al*. [3] introduced a 3D indoor emergency evacuation framework, in which a semantic model of a building is used to derive the graph network. That semantic model stored building geometry and other important building information in a graph network. Dijkstra's Shortest Path Algorithm (SPA) is used to generate evacuation paths [3].An evacuation path is the shortest possible path between an origin and a target point in distance. To generate the evacuation paths, SPAs that have the capability to calculate the shortest possible way between two points on a graph network are used. Graph networks are composed of points, and lines that connect adjacent points. Points in the network are called nodes, while lines are called edges. Each edge has a value, which is known as edge cost. In this study, edge costs were defined in terms of distances. Shortest paths were calculated according to the edge costs between the nodes. The minimum cost between an origin and a target node was the shortest path [8, 9].

Studies of Lee [4] and Lee and Zlatanova [5] explained the data model for graph network components' (i.e., node/edge) relationships and computation details. Kwan and Lee [6] studied on improving evacuation path generation efforts for response teams by integrating arriving route network and entry point uncertainties within a building with SPAs. Pu and Zlatanova [7] introduced a system for evacuation route calculation which consisted of three main parts: a geometry model that provides information

about the building's geometric features, a logical model that represents the geometric elements of the building as graph network elements (i.e. a door is represented with a door node), and a hybrid model that combines geometry and logical models. The study also included some other information items such as occupant related (i.e., age, disability level) and vulnerability information (i.e., damage status of the building). Instead of presenting a detailed study about requirements of an indoor emergency navigation system, authors evaluated current systems to determine the shortcomings. However, such an approach may not be sufficient in determining the requirements.
The models that suggest solutions to evacuation problems focus on optimization and simulation of evacuation routes and risk assessment for indoor environment [10]. Previous research studies mainly focused on the building data models, SPA improvements with semantic graph networks and vulnerability algorithms. Also, in a review study, it is stated that the trend in evacuation models is to include greater detail [10]. Thus, a detailed study for determining the requirements of an indoor emergency evacuation system is needed, as these requirements will point out the shortcomings of such systems that will increase the level of detail.

3 Use cases for indoor navigation

In this study, eleven use cases were developed to determine the requirements of indoor navigation and four of these cases are provided in this paper to describe: (1) possible events that may occur in indoor environments following a disaster/emergency situation, (2) possible triggered threats that may affect indoor environments, (3) flow of events in a building under multiple hazards, (4) behavior of the occupants following a disaster/emergency situation, and (5) working mechanism of emergency navigation algorithms. Following sections provide the details on use cases.

3.1 Assumptions and definitions

Following is the list of assumptions made during the development of the use cases:

- An up-to-date data model of buildings (i.e., BIM) that includes information about the building and its content is available.
- Indoor environments of the buildings are monitored by sensors deployed at several predefined locations in the building (e.g., corridors, stairs, and rooms).
- An indoor navigation system has been established for the buildings and it generates evacuation routes starting from exit locations of rooms (i.e., doors) and guides occupants through circulation areas in the building (i.e., corridors, stairs).
- The impacts of a disaster/emergency situation are mainly the blockage in indoor environments that prevent occupants from passing through a region and will be examined in two groups: (1) Non-accessible locations (i.e., fully/partially blocked locations) are the ones that are blocked due to the impact of the disaster/emergency situation and/or consequent threat/s. For example, collapse of a wall may block a corridor passage. (2) Vulnerable locations are the ones that contain hazardous materials and threat bearing contents, and have the possibility to cause injuries and mortality. They should be avoided during evacuation as much as possible. For example, post-earthquake fire occurred in a room causes that room to become a vulnerable location as it may cause further damage during evacuation.

- Response teams are assumed to have access to the navigation system via portable computers, hand-held computers, etc.

3.2 Use cases

Scenario #1: "Evacuation plan of a complex building following a disaster"
An earthquake affects the building in Fig. 1. Sensors in the building identifies that the earthquake triggered a fire in Room 7 and caused smoke dispersal through the corridor. Due to safety concerns, elevator is out of order. There are two exit locations from the floor; service entrance and canteen exit.

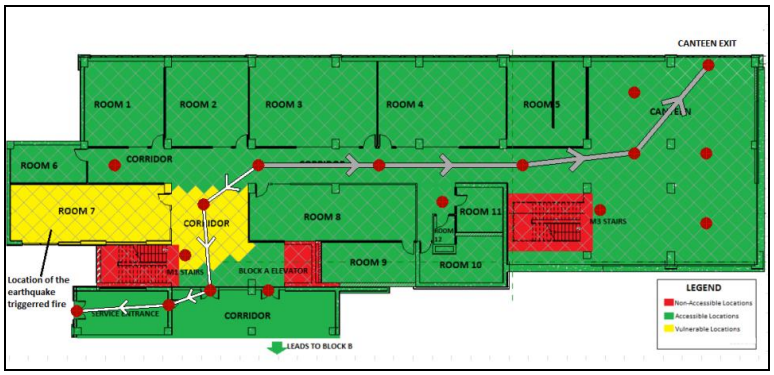


Figure 1: Floor plan with accessible and vulnerable locations and evacuation paths generated for Scenario #1

An occupant encounters the earthquake and consequent fire in Room 2 and tries to leave the building afterwards. However, occupants are not familiar with the building and thus, they need guidance for evacuation. At this point, navigation system computes the shortest evacuation path from the floor and generates the shortest path shown on Fig. 1 with white arrows. To avoid the vulnerable locations created by the fire, system generates a second path shown with grey arrows, which is longer but does not include vulnerable locations. The occupants follow this new path to leave the building safely.
Scenario #2: "Evacuation plan of a complex building when all possible exit locations are completely blocked following a disaster"
All possible exit locations are completely blocked due to an earthquake. The occupants are spread in the building searching for an exit. Meanwhile, an explosive content creates a vulnerable location in the building. Some occupants are close to that location and unaware of the risk since they lack the vulnerability information. The response team is having difficulties since the occupants are apart from each other. At this point, the indoor emergency navigation tool generates evacuation paths that lead all occupants to a relatively safer location (i.e., shelter), thus protecting them from the risks and dangers in the building. Occupants follow these paths to reach to the shelter in the building. The response team reaches the shelter and rescues all occupants immediately.
Scenario #3: "Evacuation plan of a complex building when exit locations are partially blocked following a disaster"
Both of the two possible exits of the building (i.e., service entrance and canteen exit) are partially blocked after an emergency (Fig. 2). An occupant close to Room 5 begins to search for an exit. Meanwhile, the navigation system discovers that the exit that is closer (i.e., canteen exit) has a higher blockage ratio than the further exit (i.e., service entrance). Therefore, the system generates an evacuation path towards the further exit with the lower blockage ratio.

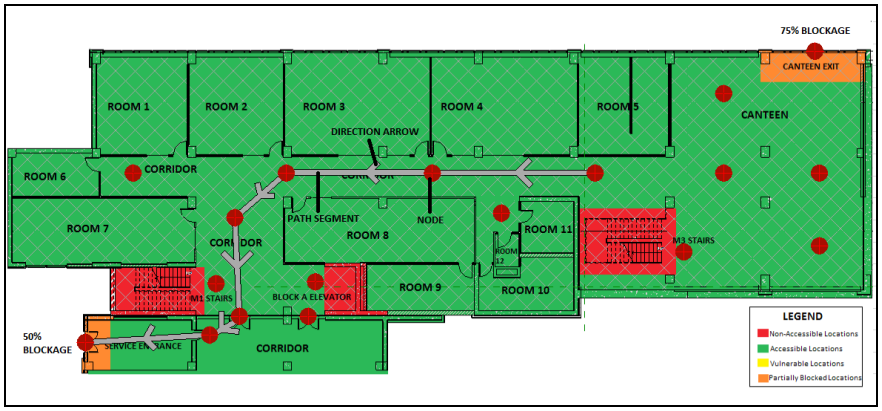


Figure 2: Floor plan with accessible locations and evacuation path generated for Scenario #3

Scenario #4: "Evacuation plan of a complex building when vulnerable locations cannot be avoided"
An earthquake triggers consequent threats that affect the indoor environment (i.e., fire, explosion) and evacuation paths cannot avoid the vulnerable locations caused by those threats. Evacuation path of an individual has two alternatives: (1) guiding the individual through a fire, (2) going through an explosive storage area with high possibility of explosion. In this case, navigation algorithm performs guidance based on the predefined vulnerability risk ranking which prioritizes all possible consequent threats that may occur in the building according to the risk contained by threats. The risk is the possibility of each threat to cause injuries and mortality. This ranking need to be prepared according to the literature review and interviews with response teams (e.g., fire fighters) and the results will be integrated with the navigation algorithm. In this scenario, the system identifies that a vulnerable location due to a fire is less preferable than a vulnerable location caused by explosion possibility. Therefore, the evacuation path that guides the individual through explosive storage area is selected even though it is longer.

3.3 Requirement analysis

The requirement analysis is performed to determine the needs of an indoor navigation system and, common navigation needs based on the use cases developed. In this study, an emergency indoor navigation system is envisioned to be composed of shortest paths to generate evacuation paths and include non-accessible and vulnerable location preventing algorithms. Thus, the determined requirements are given in three groups: (1) requirements related to shortest path algorithms and graph networks, (2) requirements related to accessibility, and (3) requirements related to prevention of vulnerable location.

3.3.1 Requirements Related to Shortest Path Algorithms and Graph Networks

SPAs and graph networks are the most important components in an emergency navigation algorithm. Thus, the requirements for these components should be considered in an evacuation system.
Requirement 1: A maximum and a minimum distance value should be set for the distance between two adjacent nodes. These distances should be determined according to the coverage areas and other limitations of the sensors that are used for sensing the indoor environment.

Reason: The distance between two adjacent nodes should not be very large because blockages or threats in the indoor environment cannot be identified effectively when the area to be sensed by the sensors increases. This leads to a decrease in the accuracy and safety margins of evacuation paths. On the other hand, the distance between two adjacent nodes should not be very small since it becomes costly to calculate the shortest path. The number of iterations needed for calculating the shortest path increases as the number of nodes and edges in the area to be sensed grows larger. Therefore, maximum and minimum distances for adjacent nodes should be set considering the sensor coverage areas. Another point in determining the distance between two adjacent nodes is that, the area represented by a node will be covered by sensor(s) to detect any blockage and/or vulnerability in the area. Sensors will be attached to sensor mainboards where they transfer data to the navigation system. However, the number of sensors that can be attached to a sensor mainboard is limited depending on the type of the mainboard. As the distance between two adjacent nodes increases, the area to be covered by sensors grows, so as the number of sensors to gather accurate data about the area. Thus, sensor mainboard limitation is another issue to be considered.

Suggested Solution: The number of sensors that can be attached to a sensor mainboard and the coverage area of a sensor are limited. Thus, the building should be divided into building sub-parts and for each sub-part that is not larger than the sensor coverage areas, sensors will be attached to one mainboard. Sub-parts cannot be larger than sensor coverage areas since sensors cannot retrieve data beyond their coverage areas. The sub-parts can be created according to the building structure. For example, a sub-part area can consist of 4 columns, 2 or more structural or non-structural bounding walls, a slab, a ceiling or a suspended ceiling, and other non-structural units (e.g., cupboards). With this solution, the building will be divided into sub-parts such as corridor parts, lobby parts (Fig. 3).

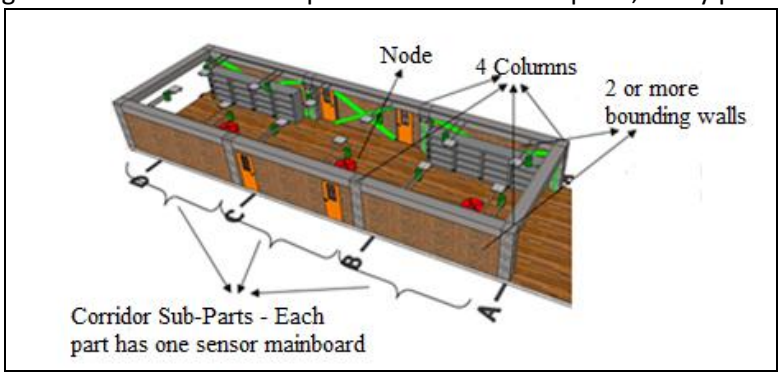


Figure 3: An example for creating building sub-parts (corridor sub-part example)

When it is not possible to define building sub-parts and place nodes within the limits of sensor mainboards and coverage areas, the distance between two adjacent nodes will be 5 meters.

Requirement 2: Alternative evacuation paths should also be calculated and ready to be used in need.

Reason: During the evacuation process, there can be events that cannot be predicted and/or sensed by the integrated guidance and assessment system. For example, a blocked location may not be sensed by the sensor network and can be classified as accessible even if it is not, or a vulnerable location may be classified as safe while it is not. Such an event may hamper the usability of the generated evacuation path.

Suggested Solution: Alternative evacuation paths should also be calculated and must be readily available for use.

Requirement 3: Each floor will have its own evacuation routes.
Reason: Evacuation is a complex process for the emergency navigation system, occupants and response teams. Changes in the accessibility and vulnerability conditions of indoor environments will also alter the evacuation paths. In case of such changes on a building floor, it is an easier procedure for the navigation algorithm to calculate a new evacuation path only for the floor considering changes, instead of making calculations for the whole building.
Suggested Solution: To decrease this complexity, each floor should have its own evacuation route. For example, a person at the second floor during a disaster/emergency situation should be guided to the shortest path that leads him/her to the stairs to the first floor. After arriving at the first floor, the navigation for this person should start from the stairs on the first floor and should be calculated separately for the first floor to find the exit.

3.3.2 Requirements Related To Accessibility

Non-accessible locations are blocked locations following a disaster/emergency situation or that are caused by a consequent threat. Along with vulnerable locations, non-accessible locations are the main determinants in evacuation path generation. The requirements for the identified cases are given below.
Requirement 4: The navigation algorithm should avoid non-accessible locations and exits.
Reason: The navigation algorithm should not guide the occupants or response teams to non-accessible locations and exits to ensure the evacuation of the building following a disaster/emergency situation.
Suggested Solution: Nodes of non-accessible locations and exits should be defined as "closed nodes" in the navigation algorithm to prevent guidance to such locations.
Requirement 5: The blockage percentage of a location under consideration should be determined.
Reason: In some cases, the building can be damaged due to the impact of the disaster/emergency situation. However, the damaged location may not be completely non-accessible and may still be used for evacuation. Such a situation can be detected by sensors.
Suggested Solution: The blockage percentage of an area can be determined by sensors. By using the data coming from different sensors and interpreting them with a probabilistic approach, the emergency system can determine the blockage percentage. Blockage percentage is, in other words, the degree of accessibility of an area in a building. For instance, an exit location may be only 10% blocked which may indicate that the exit can still be used for evacuation. By assigning a percentage to that exit, improved evacuation paths can be generated.
Requirement 6: When all exit locations are fully/partially blocked, a probabilistic guidance approach generating multiple evacuation path alternatives depending on the blockage percentages of the exit locations should be developed and integrated to the system with heuristic methods.
Reason: When there is no/partial exit out of a building, occupants tend to panic and spread around the building to find their own way out. Such an event may increase the response duration of rescue teams since they need to locate all the occupants in the building
Suggested Solution: When all the exits are completely blocked, all occupants should be guided to a safe location (e.g., shelter) until response teams arrive. If all the exits are partially blocked, the navigation algorithm should be able to select the path with lower blockage percentage even if the evacuation path gets longer. However, guidance to a distant exit with a relatively low blockage percentage (e.g., lower than 50%) would be unnecessary since evacuation would probably be possible from an exit that has blockage percentage less than 50%.

3.3.3 Requirements Related to Vulnerable Location Prevention

As explained before, vulnerable locations contain hazardous materials and threat bearing contents, and have the possibility to cause injuries and mortality. These locations should be taken into consideration by means of appropriate avoiding algorithms during evacuation path generation.

Requirement 7: The navigation algorithm should be able to avoid vulnerable locations and consider the risk levels of these locations in extreme cases, for example when all possible evacuation paths pass through vulnerable locations.

Reason: Vulnerable locations may cause further injuries and mortality during evacuation. The navigation algorithm should be able to avoid vulnerable locations due to safety reasons and select the safest vulnerable location according to the potential risk levels. For example, the navigation algorithm should be able to decide which path is safer to use when there is a vulnerable location due to a fire and a vulnerable location due to a possibility of explosion.

Suggested Solution: A heuristic method should be integrated with the navigation algorithm to avoid evacuation through vulnerable locations and the risk levels of vulnerable locations should be predefined and prioritized using heuristic methods. By increasing the cost (i.e., distance value) of an edge between two nodes by a risk value; a vulnerable location prevention mechanism can be integrated with the navigation algorithm.

Requirement 8: When vulnerability levels or vulnerable locations of indoor environment changes, the navigation algorithm should adapt the evacuation paths to the changes accordingly.

Reason: During a disaster/emergency situation, a building's indoor environment can change rapidly and a blockage may occur. For example, a fire can spread to larger areas or a location with possibility of explosion may explode and these conditions will be sensed.

Suggested Solution: The navigation algorithm should be able to regenerate the evacuation paths according to the up-to-date indoor environment data under changing indoor environment.

4 Conclusions

Following a disaster or an emergency situation, there is a need for a navigation approach to guide first responders and occupants in a blocked indoor environment because of the complex architecture of buildings and various threats that may occur. To create such an approach, the requirements of a navigation system need to be determined. For determining the requirements, multiple use cases related to disaster and emergency situations are developed for complex buildings. The requirements that are related to shortest path algorithms, graph networks, accessibility, and vulnerability are elicited from the use cases. Some of the requirements provided in this study can be listed as determining the blockage percentages, using heuristic methods for alternative evacuation path generation depending on the blockage percentages and performing vulnerability risk ranking to select the safest evacuation alternative. This study provides a basis for further studies that aim to create a navigation approach and an indoor emergency navigation system. The future work includes the creation of indoor navigation tools which are capable of generating evacuation paths, considering the accessibility and vulnerability in the indoor environment.

Acknowledgements

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