First Responders Space Subdivision Framework for Indoor Navigation

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***Abstract*—Indoor navigation is crucial, particularly during indoor disasters such as fires. However, current spatial subdivision models struggle to adapt to the dynamic changes that occur in such situations, making it difficult to identify the appropriate navigation space, and thus reducing the accuracy and efficiency of indoor navigation. This study presents a new framework for indoor navigation that is specifically designed for first responders, with a focus on improving their response time and safety during rescue operations in buildings. The framework is an extension of previous research and incorporates the combustibility factor as a critical variable to consider during fire disasters, along with definitions of safe and unsafe areas for first responders. An algorithm was developed to accommodate the framework and was evaluated using Pyrosim and Pathfinder software. The framework calculates walking speed factors that affect the path and walking speed of first responders, enhancing their chances of successful evacuation. The framework captures dynamic changes, such as smoke levels, that may impact the navigation path and walking speed of first responders, which were not accounted for in previous studies. The experimental results demonstrate that the framework can identify suitable navigation paths and safe areas for first responders, leading to successful evacuation in as little as 148 to 239 seconds. The proposed framework represents a significant improvement over previous studies and has the potential to enhance the safety and effectiveness of first responders during emergency situations.**

Keywords—Space subdivision; indoor navigation; first responders; indoor disaster

I. Introduction

Most of human life is spent indoors rather than outdoors. The average time spent indoors was 87%[1]. The increasing concentration of human populations in modern urbanized societies has aggravated the frequency and destruction of natural and artificial disasters. A United Nations study indicates that by 2050, 66% of the world's population is expected to be urban. Hence, buildings are increasingly significant, broad, and complex to accommodate them and guarantee all the requirements for protection and good well-being [2]. Buildings have been the primary focus of recent disasters, resulting in heavy damages and losses for public and emergency managers.

Residential building fires and fire deaths tend to increase yearly [3]. The increasing concentration of human populations in modern urbanized societies has aggravated the frequency and destruction of natural and manmade disasters. First responders are critical in responding to indoor emergencies, such as those in high-rise buildings. First responders, also called emergency responders, are those in charge of saving lives, protecting property, and keeping the environment safe in the early stages of an accident or disaster[4]. In large or complex buildings, it can be difficult for first responders to navigate through the entire building at once, particularly in an emergency where time is of the essence. Indoor navigation is a critical aspect of emergency response. It allows first responders, such as firefighters and emergency medical technicians, to locate and assist those in need within a building or other indoor space quickly and safely.

To effectively navigate an indoor space, first responders need to locate themselves accurately within the space and determine the most efficient route to their destination. Indoor navigation can help first responders more quickly and efficiently navigate the building, allowing them to focus on responding to emergencies and providing assistance to those in need[5]. Indoor navigation is particularly challenging because buildings can be complex, with multiple floors, rooms, and corridors, making it difficult to determine one's location and direction. This is further complicated by the presence of smoke, low visibility, and other hazards that are often present during an emergency.

In an emergency, first responders must determine the safest route through the building to reach their destination as quickly and safely as possible. This may involve considering the combustibility of the building materials, the presence of hazards or obstacles, and the location of windows or other alternative exits. In large or complex buildings, it can be difficult for first responders to navigate through the entire building at once, particularly in an emergency where time is of the essence.

One approach to improving indoor navigation for first responders is using space subdivision. This technique involves dividing a building or other indoor space into smaller, more manageable units or sections, making it easier to navigate and orient oneself within the space. In addition to improving navigation, space subdivision can also help to improve communication and coordination among first responders. By dividing the space into smaller units, it becomes easier to provide specific and accurate directions and instructions and to communicate the location and status of individuals or resources within the space. The goal of space subdivision is to provide first responders with detailed, real-time information about the layout and occupancy of a building, which can help them to reach the scene of an incident more quickly and safely.

In emergencies, there may be dynamic changes in the building, such as the spread of fire or smoke. It can be crucial for first responders to continuously update their navigation system to reflect these changes to stay safe and reach their destination as quickly as possible. Space subdivision can be used to identify which areas of the building are safe to navigate at any given time and to provide real-time updates to the navigation system.

In emergencies, first responders must determine the safest route through the building to reach their destination as quickly and safely as possible. Space subdivisions can be used to identify spaces with lower combustibility or windows that can be used as alternative exit routes and to determine the safest route through the building based on these characteristics. Overall, space subdivision can support indoor navigation for first responders in emergencies by allowing them to focus on navigating through smaller, more manageable areas of the building and staying safe.

Subdividing indoor areas is an important part of scene analysis that is used for a wide variety of purposes, including but not limited to navigation and evacuation planning [6]. Space Subdivision plays a vital role in indoor navigation [7]. The division of space in indoor navigation is basically to determine navigable and non-navigable spaces.

To improve the accuracy and efficiency of indoor navigation, current spatial subdivision models need to reflect the indoor context's dynamic changes ultimately. However, they also need help defining precise navigable space [8]. When responding to emergencies, first responders must be aware of the unexpected dynamic changes in indoor space. Hence a subdivision structure of indoor space that adapts to varied indoor spatial features and spatiotemporal dynamics is of considerable importance [9].

Several previous studies have discussed the space subdivision for indoor navigation. However, these studies have yet to reflect the dynamic conditions that often change when a disaster occurs in a building, especially during rescue operations by first responders. For this reason, this study proposes a space subdivision framework for indoor navigation for first responders.

This research aims to provide a new framework for indoor navigation that is specifically designed for first responders in emergency situations. This framework is based on the idea of dividing indoor spaces into smaller subspaces, which can be more easily navigated and searched by first responders. Some potential benefits of this approach are:

1) Improved efficiency: The proposed framework can help improve the efficiency of first responders during emergency situations. By providing a more structured and organized approach to navigating indoor spaces, first responders can quickly and efficiently locate individuals who need help or identify potential hazards.

2) Enhanced safety: The subdivision of indoor spaces can also help improve the safety of first responders by allowing them to more easily identify potential hazards, such as structural damage or chemical spills. This can help reduce the risk of injury or harm to both first responders and those they are trying to help.

The main contributions of this research include the development of a novel framework for indoor navigation that takes into account the dynamic changes of the indoor context during fire emergencies, as well as the identification of suitable navigation paths and safe areas for first responders. The framework also incorporates an algorithm that is tested using Pyrosim and Pathfinder software, which calculates the walking speed factor and affects the path and walking speed of first responders. The experimental results demonstrate that the proposed framework can improve response times and increase the chances of successful evacuation for first responders.

The implications of this research are significant, as it can improve the safety and effectiveness of first responders during rescue operations in indoor environments. By accounting for dynamic changes in the indoor context, the framework can identify suitable navigation paths and safe areas for first responders that may not have been considered in previous research. The framework has the potential to become an essential tool for emergency response teams, enhancing their ability to navigate indoor environments during emergencies and improving their chances of success.

This rest of this article is organized as follows: Section II provides a review of related work. Section III outlines the proposed framework for indoor navigation, which involves dividing the space into smaller sections. Section IV goes into further detail about space subdivision and network derivation. Section V explains the algorithm used for path planning. Section VI describes the experiments that were conducted. Section VII presents and discusses the results of the implementation. Finally, Section VIII concludes the research by summarizing the findings and outlining future research directions.

II. RELATED WORK

Some literature has extensively investigated the subdivision of space for indoor navigation. The approach usually uses well-defined building construction spaces such as rooms and corridors, builds connectivity between these spaces that use their semantics, and applies Poincaré Duality to obtain navigable networks [10]. Several semantic models have been established in this context to help with space identification and develop a navigation network [11]. The generation of an effective navigation network heavily depends on a reasonable subdivision of indoor space [12].

To create navigable subspaces for refined indoor navigation, indoor spatial subdivision, as the primary method of indoor space organization, has been extensively studied. The study [13] identifies four different steps necessary for a successful application for navigation through indoor spaces. The digital acquisition of available spaces (1), the structuring of acquired data (2), formalization of the data to establish relationships between different subspaces (3) and lastly applying the user requirements on the formalized and structured data (4). The subdivision of indoor space forms subspaces into smaller parts. The research [14] divides indoor spaces into navigable and non-navigable areas by considering human social behaviour at different times and then redivide the navigable space by the Constrained Delaunay Triangulation.

Several methods for partitioning the fundamental indoor space have been developed in order to construct fine-grained indoor navigable space. It is a common practice to use a dedicated strategy (such as visibility graph, Delaunay triangulation, and convex hull cell) or regular gridding (such as square, hexagon, etc.) [15] to divide an entire indoor space in order to derive a 2D navigable network. This can be accomplished in a number of different ways.

A fine-grained and context-aware subdivision framework (FSS) is proposed in [10] to remodel the relevant 3D space for the arrangement of navigable indoor environments by injecting numerous materials. This is accomplished by rearranging the components in a specific order. The FSS framework is hailed as a landmark for its ability to depict indoor human interaction behaviors to date. It is an inspiration for better indoor environment modeling and cognition-based navigation.

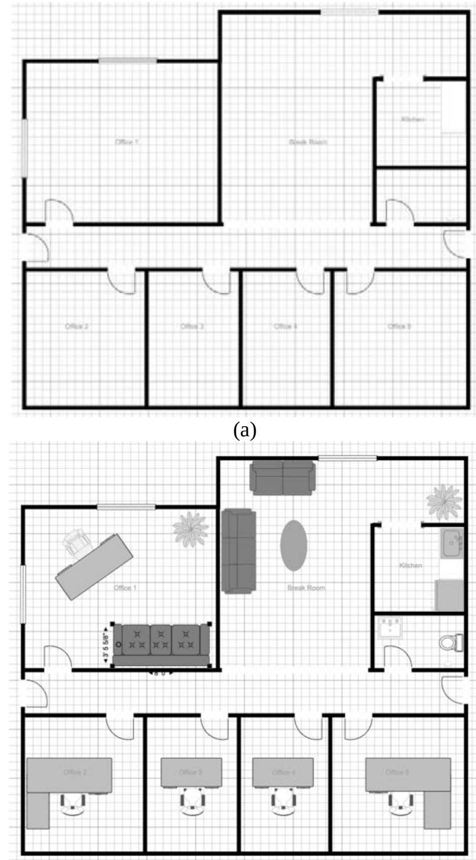
The initial formation of the F-Space considers dynamic human activities; however, their significance in the fine-grained spatial subdivision of the indoor environment is overlooked. As a result, the F-Space needs to be fully navigable possible. Within this framework, the authors separated things into three categories according to their mobility: the capacity to change their location (static, semi-mobile, and mobile). After then, the interior space, also known as the environment, was divided into three distinct sections: object space, functional-space, and remaining-space. To be more specific, object space is the non-navigable portion of subspace that is occupied by semi-mobile objects. Functional space, on the other hand, is the subspace portion dedicated to the utilization of semi-mobile objects or the activities of mobile objects and is navigable under certain conditions.

Depending on the application, subdivisions can be done on 2D or 3D levels [16]. As found in [17], there are certain advantages and disadvantages of conducting 2D and 3D subdivisions. The key advantages of 2D subdivision are that all or most calculations may be performed in 2D, the user can retain just places occupied by pedestrians in memory, and triangles are not required for vertical pedestrian placement. On the other hand, if everything is viewed as a single 3D space or pieces of 3D spaces, simulated pedestrians can freely move throughout an area without having to check to see if they have entered another space for pedestrian dynamics purposes.

III. Space Subdivision Framework

When conducting emergency rescues, first responders are often only provided with a floor plan map, even though the map already contains many objects in actual conditions, as shown in Fig.1.

However, this floor plan map may not accurately reflect the actual conditions of the space during the emergency situation. The map may have been created prior to any changes to the space or may not be detailed enough to capture all the objects or obstructions that may be present.



(a)

(b)

Fig. 1. Comparing the (a) Floor plan to the (b) Actual situation of an indoor space.

In addition, the floor plan map may not provide a clear or accurate representation of the space, making it difficult for first responders to navigate and locate individuals who need assistance. This can be especially challenging in complex indoor environments, such as large buildings or underground tunnels.

The proposed approach from this research, addresses these challenges by dividing the indoor space into smaller subspaces, which can be more easily navigated and searched by first responders. This approach provides a more detailed and accurate representation of the space, which can help first responders better understand the layout and locate individuals who need assistance.

By using a subdivision framework, the first responders can more easily identify potential hazards and obstacles within the space, which can improve their safety and reduce the risk of injury. Additionally, the framework can be integrated with existing technology, such as mapping and tracking systems, to provide real-time information on the location and movement of first responders within the indoor space.

Space subdivision can be a useful tool for indoor navigation for first responders in an indoor emergency situation, as it allows the building to be divided into smaller, more manageable areas that can be navigated separately. This can be particularly helpful in situations where there are dynamic changes in the building, such as the spread of fire or the presence of smoke, as it allows the first responders to focus on navigating through a smaller area at a time rather than trying to navigate through the entire building at once.

Here are some ways in which space subdivision can help with indoor navigation for first responders in an indoor emergency situation:

1) Identifying safe navigable spaces: By dividing the building into smaller spaces, it can be easier to identify which areas are safe to navigate based on factors such as the combustibility of the material and the presence of hazards.

2) Determining the safest route: By dividing the building into smaller spaces, it can be easier to determine the safest route through the building based on the characteristics of each space. For example, the first responders might choose to navigate through spaces with lower combustibility or with windows that can be used as alternative exit routes.

3) Providing real-time updates: By continuously monitoring the building for dynamic changes and updating the space subdivision accordingly, it can be easier to provide real-time updates to the navigation system to reflect any changes in the safe navigable spaces.

We propose a classification of interior objects based on mobility and safety for first responders as a means of subdividing dynamic indoor settings. This classification would be used by first responders. This classification expands [10] original works.

In order to get a head start on our work, we will first go over the essential definitions of indoor objects and indoor subspaces following the FSS framework from [10]. The FSS framework categorizes indoor objects as either static S-objects (such as indoor fixed structures), mobile M-objects (such as humans), or semi-mobile SM-objects. Static S-objects include indoor fixed structures. The products have been sorted into these categories according to how mobile they are. Independent of the type of building being used, the S, SM, and M-objects provide direction for the space subdivision. They are utilized in defining the geometry, semantics, and topology of the subspaces that they physically occupy or are necessary for their access or utilization. The location of these objects will determine the areas that are open for navigation and those that must be avoided.

Meanwhile, the meanings of O-Space, R-Space and F-Space have been established. O-Space is a non-navigable subspace that SM-objects physically inhabit. R-Space refers to the area of space that is open to navigation and can be traversed at will. In contrast, F-Space is a subspace functionally occupied by SM-objects or motion-less M-objects for user interactions. To be more exact, F-Spaces are spaces that are not considered navigable unless they form an essential part of the navigation system.

It is essential to have a solid understanding of how a structure would behave in the event of a fire. The establishment of minimum construction criteria is done to assist in maintaining the building's structural integrity for the amount of time necessary for evacuating the building or moving to a secure position within the building. The rate at which a fire will spread is directly proportional to the combustibility of the material it is burning. These two components are equally crucial to ensuring that both lives and property are not lost in a fire.

A building's structural integrity can be affected by a fire. Different materials have varying degrees of resistance to fire [18]. When there is a risk to the route's stability, it is impossible to travel along that route. When the length of the fire is greater than or comes dangerously close to exceeding the fire resistance duration of the building material, the stability of the route is jeopardized. Unsecured shafts or openings pose an additional risk to the safety of the firefighters and the operation as a whole, and the planning of the route should take care to avoid them.

The amount of smoke in a region affects vision, which, in turn, decides whether or not a path may be used. If a path is devoid of smoke, has adequate visibility, and is easily navigable. In certain circumstances, smoke will only be found above a predetermined height beneath the ceiling. The area below the smoke may then be free of smoke and suitable for passage.

The NFPA (National Fire Protection Association) 220 Standard on Types of Building Construction [19] defines the different types of building construction by basing it on the combustibility and the fire resistance rating of the structural parts of a building. When we speak of materials or assemblies having a specific fire resistance rating, we refer to the amount of time measured in minutes or hours that they have been able to withstand exposure to fire, as established by specific tests. In this study, we take combustibility as a factor in determining the definition of a static object by taking the categorization from NFPA 220 [19].

A. *Definition 3.1*

(Redefinition of S-objects): static (S-objects) as objects that can neither move by themselves nor be moved (e.g., construction elements such as walls, columns, stairs, etc.)[10]. In this paper it can be redefined as three types of objects based on combustibility:

- Scom (Static-Combustible) is a material that, in its intended form and under the anticipated conditions, will ignite and burn;
- Slcom (Static-limited combustible) is a material does not meet the standards for non-combustible material.
- Sncom (Static-non-combustible), in its intended form and under the predicted conditions, the material will not ignite, burn, support combustion, or emit flammable gases when exposed to fire or heat.

Still in the FSS [10], the agents are the primary dynamic actors that are considered. During the process of estimating a route and when actually navigating, the A-Spaces intend to take into account the dimensions of the objects as well as the required amount of space around them. An ‘A-Space’ is a clearance space containing one or more agents and the SM objects they carry if they have any.

This clearance space can be characterized as A-Space. However, the study [10] only considered the available free space. In rescue operations carried out by first responders, free space is taken into account, but the most important aspect is the space that is considered safe from the worst possibilities, such as fire and other hazards. The study [20] described a safety zone as "an area identified by qualities that give freedom from danger, harm, or injury". In definition 3.2, we are redefining A-Spaces by considering the conditions that may occur in rescue operations.

B. *Definition 3.2*

(Redefinition of A-Spaces): we re-identify two types of A-Spaces:

- a safe one (*AS*-Space) corresponding to the remaining space that give freedom from danger;
- a non-safe one (*ANS*-Space) corresponding to the remaining space that not give freedom from danger.

We took a case by taking a 3D floor plan of the 2nd floor of the Westport House from WRLD3D.com, and by adding a heatmap, we simulated an unsafe area caused by a fire. As seen in Fig. 2, the area given the red heatmap is ANS-Space, while the rest is AS-Space.

Fig. 2. AS-Space and ANS-Space within indoor building.

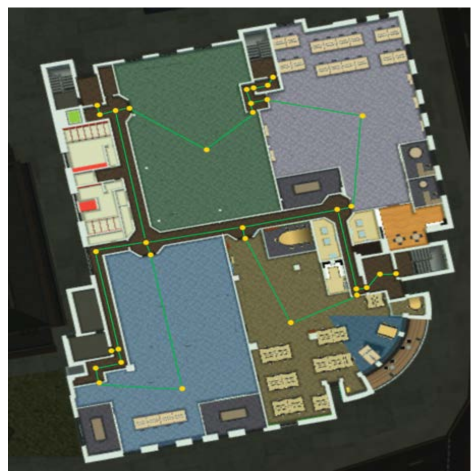
IV. Space Subdivision and Network Derivation

The navigation network is a crucial component of most navigation and evacuation approaches[21]. A navigation network in indoor navigation refers to a system of interconnected paths or routes that can be used to navigate through an indoor environment, such as a building. The navigation network may include information on the layout of the building, the location of exits, stairwells, and elevators, and the presence of hazards or obstacles. It may also include information on the characteristics of the spaces within the building, such as the combustibility of the materials, the presence of windows, or the availability of emergency exits.

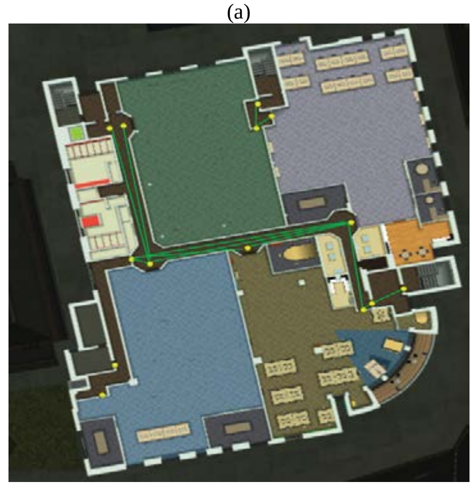
There are widely accepted methods for developing indoor navigation networks, such as medial axis transformation (MAT), visibility graph (VG), or mixtures of them [22]. In other studies, CDT (Constrained Delaunay Triangulation)[23], and generalized Voronoi diagram (GVD) are also used. In this study we use MAT and VG to create a navigation network.

Straight skeleton is the process of skeletonizing a geometric space. The straight MAT algorithm [24] generates a 3D indoor skeletal graph. Fewer vertices are added to the network, resulting in increased computing efficiency. Taneja et al. in [25] employed direct MAT to turn IFC-based data into a geometric topology network, which might serve as a navigational aid model. As can be seen in Fig. 3(a), we created a network using MAT based on the existing floor plan. While in Fig. 3(b) is the network derivation using VG.

Deriving nodes from existing building plans is the first and most essential step in developing an VG (visibility Graph)[26]. Based on their navigational functions, there are primarily two types of nodes in a VG [27]. First, a junction node denotes the intersection of at least two corridor segments. The second, portal nodes describe wall openings, such as those occupied by doors and windows in each room.



(a)



(b)

Fig. 3. Navigation network: a) MAT network and (b) VG network.

V. Path Planning

Safe routes are essential in indoor navigation for first responders because they help to ensure that the responders can reach their destination safely and efficiently, even in hazardous or challenging environments. This is especially important in emergency situations, where time is of the essence and responders may need to navigate through unfamiliar or potentially dangerous spaces. Common path findings utilizing typical navigation methods may not be sufficient in an emergency, as they may be too dangerous or unavailable due to damage. Critical in these situations is the ability of emergency and rescue professionals to find other and best routes [28].

In this study, we propose an algorithm for determining the safest path for first responders by taking into account factors such as the combustibility of materials and dynamic changes in the building such as fire. To create an algorithm for safe indoor navigation for multiple first responders that takes into account the combustibility of materials, dynamic changes in the building such as fire, and is based on space subdivision, we could consider the following steps:

1) Identify the start and end points of the route for each first responder.

2) Obtain a map of the building or structure, including information on the layout and location of rooms and corridors.

3) Divide the building or structure into smaller spaces, such as rooms and corridors.

4) Determine the combustibility of materials in each space. This information can be obtained through building codes or by consulting with the building's owner or management.

5) Use the map and combustibility information to identify potential hazards in each space, such as rooms or corridors with highly combustible materials.

6) Consider the potential for structural collapse and other hazards that could block the route such us smoke.

7) Based on this information, determine safe routes for each first responder that avoids or minimizes exposure to potential hazards. This can be done by selecting paths through the building or structure that avoid spaces with high hazards and maximize the use of spaces with low hazards.

Here is the pseudocode of our proposed algorithm:

```
PROCEDURE findSafeRoutes(starts, ends, map, combustibility)
    spaces <- list of all spaces in map
    routes <- empty list
    FOR EACH start, end IN starts, ends
      route <- empty list
      currentSpace <- start
      WHILE currentSpace != end
        nextSpace <- null
        lowestRisk <- infinity
        FOR EACH neighbor IN neighbors of currentSpace
          totalDistance <- distance between currentSpace and neighbor
          totalHazardExposure <- 0
          riskOfCollapse <- 0
          IF neighbor has highly combustible materials
            totalHazardExposure <- totalHazardExposure + 1
          IF neighbor is at risk of structural collapse
            riskOfCollapse <- riskOfCollapse + 1
          IF neighbor is on fire or has high levels of smoke
            totalHazardExposure <- totalHazardExposure + 10
          IF neighbor is a window and is suitable for exiting the building
            totalHazardExposure <- totalHazardExposure - 5
          totalRisk <- totalDistance + totalHazardExposure + riskOfCollapse
          IF totalRisk < lowestRisk
            lowestRisk <- totalRisk
            nextSpace <- neighbor
        route <- route + (currentSpace, nextSpace)
        currentSpace <- nextSpace
      routes <- routes + route
  RETURN routes
```

This pseudocode defines a procedure findSafeRoutes that takes as input the start and end points of the routes for each first responder, a map of the building or structure, and information on the combustibility of materials in the building. The procedure returns a list of routes as output. The algorithm determines the safest route for each first responder by traversing the spaces in the building or structure, calculating the total distance, total hazard exposure, and risk of structural collapse for each possible next step, and selecting the step with the lowest total risk as the safest route. If a space is on fire or has high levels of smoke, the algorithm increases the total hazard exposure to prioritize avoiding these spaces. If a space is a window that is suitable for exiting the building, the algorithm decreases the total hazard exposure to prioritize using this space as an alternative exit. The algorithm continues this process until the end point is reached.

VI. Experiment

An agent-based simulation is a well-established technique for modeling various applications, including evacuations[29]. ABM (Agent-based modelling) is a simulation technique in which an entity functions as an agent. The rules set, interactions with other agents and the surrounding environment determine the behavior of individual agents. These simulations can be used to test and evaluate different evacuation strategies, communication protocols, and other emergency response procedures in a safe and controlled environment. The simulation can be used to test different scenarios and evaluate the performance of the first responders. It can also help identify bottlenecks in the evacuation process and evaluate the effectiveness of different communication and coordination strategies. The results of the simulation can be used to improve training for first responders and to develop more effective emergency response plans.

In this research, Pathfinder is combined with Pyrosim. The smoke display file is imported into the FDS simulation parameter data. FDS integration and passenger delay in smoke were investigated to allow ABM to limit agent speed due to smoke. In this study, the experiment was carried out in a six-story building, as seen in the Fig. 4.

The data we use uses the floor plan provided on Pathfinder. First, the IFC file is imported into Pyrosim to then create a building geometry model. In Pyrosim, we set a fire point with a power of 800.0 kW/m², which is placed in a room on the 3rd floor of the building as shown in Fig. 4.

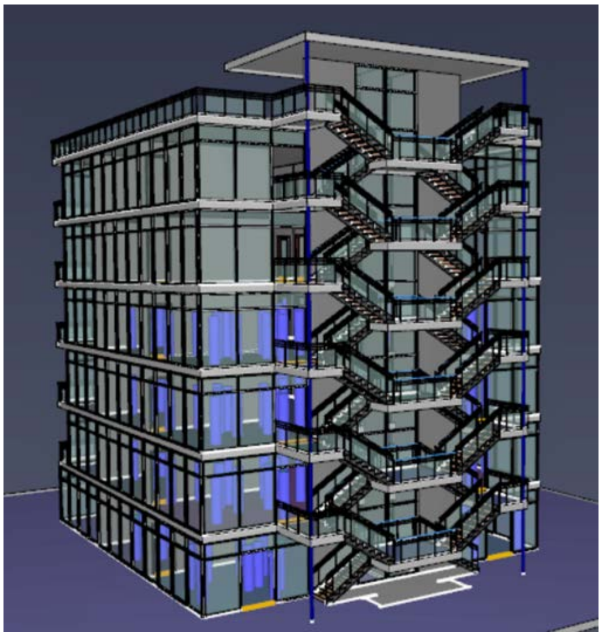


Fig. 4. Case study buildings.

Four visibility devices were installed in the building to record changes in the building's smoke levels. The bigger the smoke, the higher the total hazard exposure, as in the algorithm we proposed, which will increase the total risk.

In Fig. 5 we can see a fire simulation that occurred in the building. Smoke can affect the walking speed of first responders during an indoor evacuation by limiting visibility and making it difficult to navigate through the building. Smoke inhalation can also cause respiratory distress, which can slow down first responders. Additionally, the heat generated by a fire can make it physically challenging for first responders to move quickly through the building. This can be dangerous as it can cause them to become disoriented and lost, making it more difficult to evacuate the building and rescue those inside.

Visibility will be used to slow down people's walking speed. To achieve this, visibility will be measured in several areas within the model. The measurement location will be along the evacuation route, preferably stored on the floor where the fire occurred. Using the visibility distance measured at the location, the local velocity factor will be generated as a function of time. Responders will then reduce their speed and modify their route accordingly. [30] provides a walking speed function as a function of visibility. This is referred to as absolute walking speed in the paper, but we will treat it as a factor that slows the speed of each occupant. Fig. 6 depicts a linear relationship between walking speed and visibility, which can be expressed by the Eq. (1):

$$Walkingspeed = min(1, max(0.2, 1-0.34 * (3-vis))) \quad (1)$$

In Fig. 7, we can see the extracted navigation mesh from one of the floors of the building. This navigation mesh will be useful for responders in determining routes.

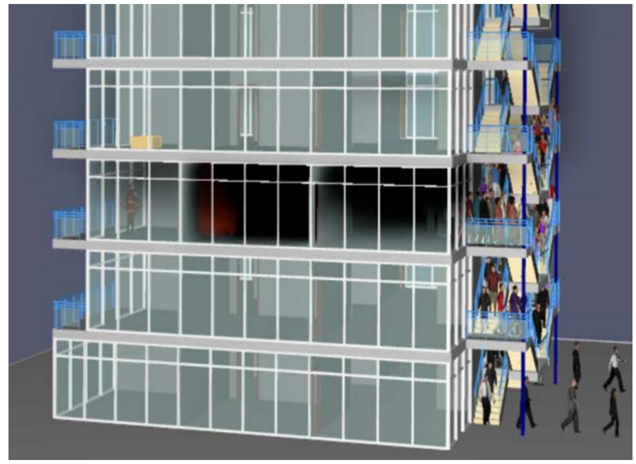


Fig. 5. Fire simulation scene in the building.

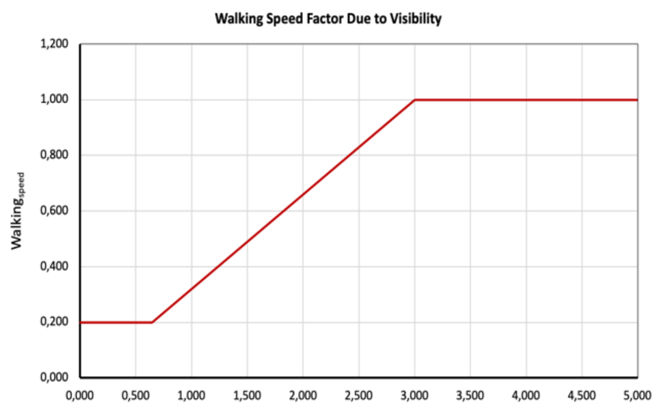


Fig. 6. Walking speed factor due visibility.

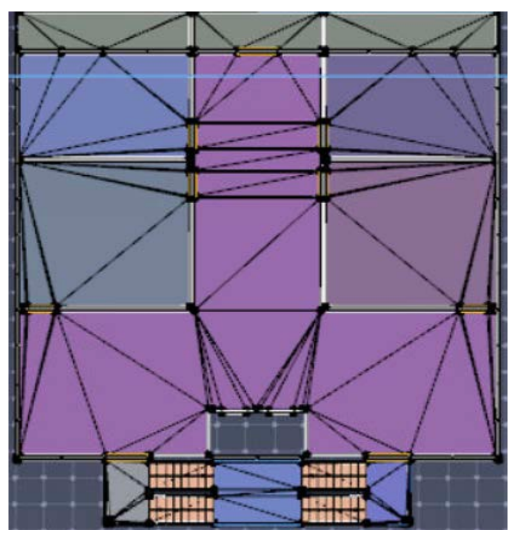


Fig. 7. Extracted navigation mesh.

Navigation mesh space subdivision is a method of breaking down an indoor environment into smaller, manageable sections for the purpose of pathfinding and navigation. This can be particularly useful for first responders, who may need to navigate through large, complex indoor environments such as buildings, airports, or shopping malls. By breaking down the environment into smaller sections, navigation mesh space subdivision can help first responders to navigate through an indoor environment more efficiently and safely by reducing the complexity of the environment and allowing them to focus on specific areas.

The simulation of route choice in this model employs a locally quickest path planning approach. This approach involves ranking routes hierarchically based on local information such as the location of people and the waiting times at exits.

Our model uses two profiles, Occupants and Responders. The number of occupants of the building is 360 people, and 90 people inhabit each floor. Occupants were only set for four floors, while for the floor where the fire occurred, five first responders were simulated during the experiment. The decision to set occupants for only four floors and to simulate five first responders was made to maintain a manageable size for the simulation, while still allowing for a realistic evaluation of the evacuation process and the response of first responders to the emergency situation. By limiting the number of floors with occupants, the experiment could focus on the behavior of the occupants in response to the emergency and the effectiveness of the evacuation procedures. The simulation of five first responders on the floor where the fire occurred was intended to evaluate their ability to navigate the space, locate the occupants, and carry out the evacuation process. Overall, the decision to set occupants for only four floors and simulate five first responders on the floor where the fire occurred was a deliberate choice to ensure a manageable size for the experiment while still providing a realistic evaluation of the evacuation and emergency response processes.

The occupants are assigned a profile with a normal speed of 0.8 m/s to 1.2 m/s. These profiles have a zero Priority Level. The responders' profile has a constant velocity of 1.19 meters per second and a Priority Level of 1. This means in the event of a conflict during movement, and responders will be given priority. However, when going through a smoke-filled room, the pace will decrease according to the value acquired by the visibility tool and then calculated based on the walking speed factor.

VII. Results and Discussion

This section summarizes the findings of the fire simulation, with a focus on the first responders, based on the assumptions provided in the previous section. Visibility measurement tools output data to csv files. An example of measurement result data can be seen in Fig. 8. The data was generated from four visibility measurement devices during the simulation run. After the simulation, the data from the visibility measurement devices is processed using the equation shown in the Speed walking Factor to calculate the velocity factor as a function of time based on visibility.

1	s	m	m	m	m
2	Time	visibility1	visibility2	visibility3	visibility4
214	42.20	1.50	18.89	15.50	30.00
215	42.47	1.49	19.16	15.19	30.00
216	42.61	1.48	19.43	14.89	30.00
217	42.86	1.48	19.69	14.59	30.00
218	43.04	1.47	19.94	14.23	30.00
219	43.24	1.47	20.11	13.90	29.88
220	43.43	1.47	20.24	13.53	28.54
221	43.63	1.47	20.34	13.16	27.13
222	43.82	1.47	20.41	12.81	26.00

Fig. 8. Result data from visibility device measurements.

Fig. 9 shows a graph of the velocity factor resulting from the measurements.

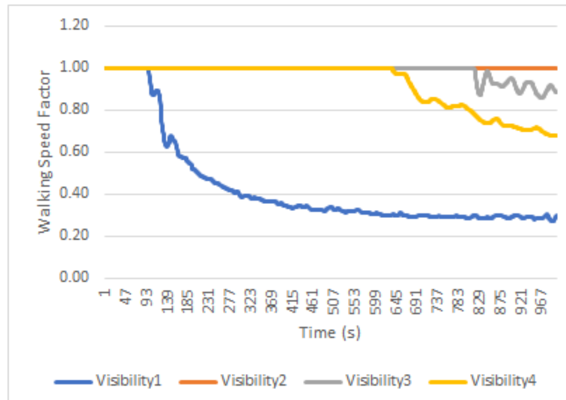


Fig. 9. Walking speed factor.

The time taken by the five responders to carry out the evacuation operation to the location where the fire/smoke occurred was measured during the simulation. The time taken for the responders to enter the building and return safely was calculated, and the results are presented in Table I. Table I compares the time required using the walking speed factor to the time that does not take the walking speed factor into account.

Table I and Fig. 10 shows that the smoke will affect the walking speed of each responder, where the speed will be slower according to the amount of smoke calculated from the visibility devices. In Table I, a non-factor column is an event where a fire does not occur and does not occur immediately. So that the walking speed of first responders is faster than when there is a fire. Smoke can greatly impact the visibility and the walking speed of first responders during indoor emergency operations. Smoke can obscure visibility, making it difficult for first responders to navigate through the environment and locate victims or exits. It also can cause respiratory issues and make it harder for first responders to move quickly through the environment. The smoke can greatly affect the walking speed of first responders, making it more difficult for them to navigate through the environment and locate victims or exits. This can have serious consequences in emergency situations, as it can delay response times and make it more difficult to rescue victims or contain fires.

TABLE I. COMPARATION OF EXIT TIME

	Exit Time (s)	
Name	**Non-Factor**	**With Factor**
Responder1	234.825	218.35
Responder2	188.275	148.275
Responder3	239.05	239.625
Responder4	226.025	219.6
Responder5	244.075	227.075

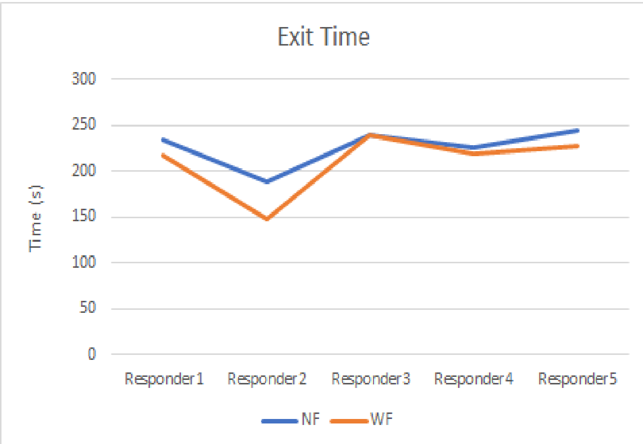


Fig. 10. Exit time from responders.

VIII. CONCLUSION AND FUTURE WORK

The present study introduces a new framework for space subdivision in indoor navigation specifically developed for first responders. The framework expands upon previous research by including the combustibility factor as a key variable to consider in the event of a fire disaster in a building. Additionally, definitions of safe and unsafe areas for first responders were incorporated based on factors such as the level of hazard and smoke concentration. From these definitions, an algorithm was developed to accommodate the framework, which was then evaluated using Pyrosim and Pathfinder software. Pyrosim was utilized to create a fire model that was measured using a visibility device. The resulting measurements were then subjected to a walking speed factor calculation, which affected the path and walking speed of the first responders. The proposed framework enhances the response time and increases the chances of successful evacuation for first responders, ultimately improving their safety and effectiveness during rescue operations in indoor environments.

Unlike previous studies on indoor navigation, the proposed framework captures dynamic changes such as smoke levels that can impact the navigation path and walking speed of first responders. The experimental results demonstrate that the five simulated first responders were able to complete the evacuation process within 148 to 239 seconds when the fire occurred at a specific location in the building. By accounting for dynamic changes in the indoor context, the proposed framework can identify suitable navigation paths and safe areas for first responders that may not have been considered in previous research. Thus, the proposed framework represents a significant improvement over previous studies, and has the potential to enhance the safety and effectiveness of first responders in emergency situations.

Future works from this research: integrating the proposed framework with other technologies, such as augmented reality, virtual reality, and internet of things (IoT), to enhance the navigation experience for first responders. Enhancing the cost function: The study should consider more factors in the cost function such as the time consumed by the first responders, the physical strain on them, and the risk of injury. Real-time monitoring: The study could explore the implementation of real-time monitoring systems to track the first responders' movements and provide them with real-time guidance.

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