1-1-2021

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Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 184 (2021) 218–225

Procedia Computer Science

www.elsevier.com/locate/procedia

The 12th International Conference on Ambient Systems, Networks and Technologies (ANT)
March 23-26, 2021, Warsaw, Poland

A smart dynamic crowd evacuation system for exhibition centers

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Abstract

In this paper, we consider the problem of finding the safest evacuation route in a multi-exit exhibition center while the fire hazard spreads. We first propose a system composed of sensor nodes to collect pertinent safety data. We present a real-time dynamic evacuation system that considers the changing conditions in the risks associated with each hallway segment in terms of walking distance, heat, two major asphyxiant fire gases and congestion. Our system activates smart panels placed at major junctions of the hallways to guide evacuees towards the appropriate exit by displaying the proper escape direction. This work can pave the way towards the development of next-generation smart exhibition centers, where crowd safety is among the top priorities.

Keywords: Smart exhibition center; crowd management; evacuation system; indoor navigation; fire evacuation

1. Introduction

Hundreds of international trade fairs and exhibition events are organized each year. Despite the large space availed to visitors in most exhibition centers, the sheer number of attendees often result in transient crowd congestion situations that need to be carefully managed, especially during crisis situations such as fire blazes, bomb threats, armed assaults, or terrorist attacks.

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10.1016/j.procs.2021.04.004

Exhibition centers are not prone to fires as demonstrated for instance by the massive blaze at the SkyCity convention center in Auckland in October 2019. As a result, effective emergency response mechanisms must be put in place to swiftly assist in the evacuation of the attendees to save lives and reduce potential injuries due to people stumbling and trampling.

Motivated by above, we propose a dynamic and smart evacuation model for multi-exit exhibition centers in the presence of spreading fire blaze. Our dynamic evacuation provides visual indications to evacuees to guide them towards best available paths while trying to circumvent dangerous zones. This work is part of the *Ariadne* “Smart Exhibition Center” project that aims to pave the way towards intelligent exhibition centers by leveraging the usage of mobile computing, wireless sensors, image processing, and artificial intelligence.

Our approach addresses many limitations associated with most earlier contributions notably (1) the reliance on static fire hazard models, (2) the usage of static evacuation models that do not adapt to dynamic fire spreading behavior, (3) the narrow choice of parameters to characterize the risk associated with a given hallway, and (4) the non-applicability of the approach to real-life scenarios.

The remaining of this paper is organized as follows: In Section 2, we present a review of major related studies and highlight the contribution of this research. Section 3 presents the proposed approach, while section 4 outlines our simulation environment and scenarios. Finally, in section 5 we provide a summary of the paper and some recommendations for future research.

2. Related work and research contribution

Various approaches have been proposed to calculate the best suited escape route in the case of single as well as multiple emergency-exits. Most of these approaches operate on a graph-based model and they differ in terms of many aspects, including:

- The graph modeling approach as reflected by the choice of the vertices and edges
- The choice of the weights assigned to each vertex and the capability to handle dynamically changing routes
- The choice of the algorithm to find the most suitable evacuation route
- The general approach: optimization-oriented or computer simulation-oriented
- Implementation approach: spontaneous evacuation plan versus organized evacuation plan [1]
- The architecture of the proposed solution (centralized versus distributed)

Filippoupolitis and Gelenbe [2] proposed a distributed system that computes the best evacuation routes, while a hazard is spreading inside a building. The weight of each edge is the product of two variables: the physical length of the edge and the intensity of the associated hazard along the edge. However, the hazard intensity values collected from the sensor nodes remain undefined and it is not clear how these were used in the simulation model.

Shikhalev et al [3] proposed a decision support system to determine the safest route during an emergency. They formulated a multi-objective optimization model where the weight of each section in the route considers three criteria: obstruction (based on people density), timeliness (based on the fire hazard value) and length (based on the length of the section). The approach, however, is not suitable for implementation in real-life settings as (1) it aims to calculate the safest escape route for each person from his starting position to each safety areas which is not practical, and (2) the solution is sensitive to various parameters including the value of the fire hazard on each section (which is not defined) and the weight coefficients associated with the cost of each edge.

Atila et al [4] proposed a mobile dynamic fire evacuation system. The microscopic model calculates the personal route for each evacuee by considering his/her individual route and provides visual instructions on the smartphone to guide each evacuee towards the exit. Based on earlier studies on smartphone usability and human psychological reactions during emergency evacuations (e.g.[5]), we argue that the usage of mobile apps for evacuation is not practical due to the additional cognitive load imposed on users while they struggle to evacuate themselves.

There have been works focusing on the study of spontaneous evacuation models [1], including dynamic minimum-cost flow network models [6], evolutionary algorithm [7], ant colony optimization [8], and Capacity Constrained Router Planner (CCRP) heuristic algorithms [9], among many others. Each of these approaches has its own merits and drawbacks. For a review of the relative merits of these (and other) approaches, the reader is referred to the survey paper of Ibrahim et al [10].

Our approach is based on a spontaneous evacuation plan that can adapt to changing conditions and operates at the macroscopic rather than microscopic (individual) level. Hence it does not require each evacuee to be equipped with a special device (such as a hand-held RFID reader as suggested in [4]) to acquire his location in real-time. Recall that microscopic models consider the evacuee's individual characteristics and interaction in the evacuation process, while macroscopic models are often based on network flow models [1].

Our contribution includes the following:

- A new graph model whereby hallway sections are modeled as links and junctions are modeled as nodes.
- A new approach for determining the escape plan. In our case, once a fire occurs, we measure the risk index of each hallway section at regular time intervals and direct evacuees at the junctions based on shortest path algorithm that aims to reduce the total risk along the evacuation pathway, as opposed to merely trying to minimize the total evacuation time, which could put evacuees at risk due to exposure to excessive heat or suffocation.
- The adoption of a more realistic model in computing the cost associated with each hallway section, which includes not only the distance but also the risk associated with high temperature, level of toxic gases, and congestion levels.
- The usage of constrained based routing algorithm which prunes links that do not satisfy the minimum safety requirements prior to computing shortest paths.
- A mechanism to dynamically adjust the evacuation routes according to the evolving status of the fire propagation and the dynamic nature of crowd density during the evacuation.
- The reliance on visual direction indicators, displayed on smart digital panels located at the junctions of hallways to guide evacuees towards the safer exits

3. Proposed approach

We first outline the design aspects of the proposed system, including its underlying assumptions and the graph modeling approach being pursued.

3.1 General assumption

Our proposed approach is based on the following assumptions:

- The detailed floor plan/layout of the exhibition center is known a priori
- There are several sensor nodes installed at specific locations along the hallways of the exhibition center. For better fault tolerance, we adopt dual base station architecture for the Wireless Sensor Network (WSN) in a star-of-stars topology. The sensor nodes communicate with the two base stations (BS), which forward the collected data to a network server.
- Each sensor node collects and sends real-time information to the base station which includes temperature, Carbon monoxide (CO), hydrogen cyanide (HCN) and crowd density levels.
- There are several smart digital panels at the junctions of the exhibition center (in each direction) which provides emergency signage in the form of a dynamic visual indicator.
- An application (Command and Control) server is put in place to communicate with the central server and to calculate the most suitable evacuation route to the most appropriate emergency exit. The Command and Control server conveys the suggested evacuation direction to each junction via the corresponding smart digital panel.

Fig.1 illustrates a simplified diagram of the system architecture

3.2 Graph modeling approach

We illustrate the problem formulation, the modeling and solution approaches with the example depicted in Fig.2. As may be seen, the layout shows various stands (greyed boxes) and four emergency exits. The red circles correspond to the crossings of escape routes (major junctions) where smart digital panels are located to indicate the evacuation direction. The above plan is modeled by the graph G (N, E) depicted in Fig. 3.

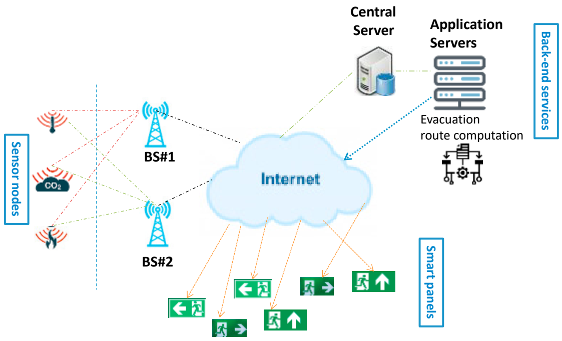

Fig.1. Simplified diagram of the system architecture

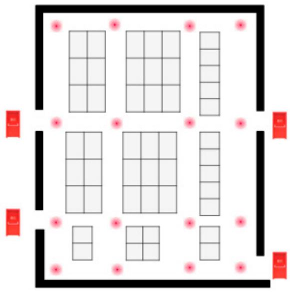

Fig.2. Illustrating example for the floor plan of an exhibition center

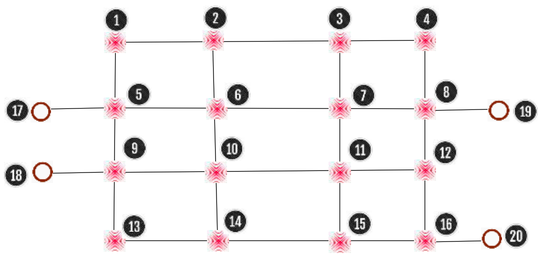

Fig.3. Graph modeling the plan shown in Fig.2

The graph consists of a set of 20 vertices where vertices 1-16 correspond to the crossings of escape routes (coinciding with the locations of the digital panels) and vertices 17-20 correspond to the four emergency exits. These vertices will be thereafter referred to as regular and exit nodes, respectively. The graph also consists of 28 edges, each corresponding to a potential leg (hallway) along feasible escape routes that evacuees can follow. For each edge connecting nodes i and j, we associate a time-dependent weight value $W_t(i,j)$which represents the cost of using link (i,j) at time t to escape towards one of the exits.

In our case, $W_t(i,j)$is defined as a weighted average, according to the following expression:

$$W_t(i,j) = \alpha_1 L(i,j) + \alpha_2 P_t^T(i,j) + \alpha_3 P_t^{CO}(i,j) + \alpha_4 P_t^{HCN}(i,j) + \alpha_5 P_t^D(i,j)$$

where the weight coefficients $\alpha_i \in [0,1]$ sum up to 1. These coefficients reflect the relative importance of the associated variable in the evacuation decision making process.

In the above equation, $L(i,j) \in [0,1]$ represents the relative length of hallway segment (i, j), defined as the ratio of the length of link (i,j) to the length of the longest link in the graph. The terms $P_t^X(i,j) \in [0,1]$ correspond to the risk index $RI \in [0,1]$ associated with the temperature (T), Carbon monoxide (CO), hydrogen cyanide (HCN), and people density (D), as further explained below.

In our case, some sensors are installed along each hallway section *(i,j)*. These sensors monitor various parameters that are used as proxy-indicators of the risk associated with selecting hallway segment *(i,j)* in the escape route. More precisely, we monitor the following environmental and congestion-related parameters:

- Temperature: Each reported temperature value is converted into a risk index $P_t^T(i,j)$ according to table 1. The ranges are inspired from the empirical work of Willi et al [11].

Table 1. Temperature - risk index conversion

Reported temperature T (ºC)	Risk classification	Risk index
T < 48	Low	0
48 ≤**T** <50	Medium	0.5
50 ≤ **T** < 150	High	0.7
T ≥ 150	Very high	1

- Toxic (Asphyxiant) fire gases which include Carbon monoxide (CO) and hydrogen cyanide (HCN). Together, CO and HCN – recognized in the fire industry as the “toxic twins” – create a deadly chemical asphyxiant that can put fire victims into cardiac trauma [12].

  Carbon monoxide poisoning is the most common type of fatal air poisoning during fire as carbon monoxide asphyxiation has been a leading cause of deaths for those overcome by smoke. The ranges for CO levels are based on the Acute Exposure Guideline Levels (AEGLs) for exposure times of 10 minutes and 30 minutes [13]. For instance, exposure for 10 minutes to a level of CO at or above 420 ppm can yield serious long-lasting effects or impaired ability to escape [13].

  CO reported values are converted to risk index $P_t^{CO}(i,j)$ according to table 2.

Table 2. CO level – risk index conversion

Reported CO level (ppm)	Risk classification	Risk index
CO < 150	Low	0
150 ≤**CO** <420	Medium	0.5
420 ≤ **CO** < 600	High	0.7
CO ≥ 600	Very high	1

  Hydrogen cyanide (HCN) is a colorless, rapidly acting, highly poisonous gas that is 35 times more toxic than CO [14]. The ranges for HCO levels depicted below are derived based on the studies reported in [14]. HCN reported values are converted to risk index $P_t^{HCN}(i,j)$ according to table 3.

Table 3. HCN level – risk index mapping

Reported HCN level (ppm)	Risk classification	Risk index
HCN < 36	Low	0
36 ≤**HCN** <108	Medium	0.5
108 ≤ **HCN** < 135	High	0.7
HCN ≥ 135	Very high	1

- Congestion (crowd degree), as measured by human density, is a determinant factor of crowd dynamics and evacuee’s walking speed, and hence it has strong influence on the evacuation time [4]. The density, D, along a given hallway section is estimated as the number of people inside its circulation divided by the area. To determine the number of visitor present in each hallway, we recommend the usage of IR transmitter and receiver pairs as it is reliable, and it provides a low-cost, yet accurate solution method. The ranges for the density ranges depicted in table 4 were derived based on the results reported in [10]. For instance, a density of 7.1 persons/m^2 corresponds to the maximum crowd density while standing. Human density values are converted to risk index $P_t^D(i,j)$ according to table 4.

The weights α_i were determined based on reported fire and rescue statistics and expert judgements as follows:

In [15] it was highlighted that HCN is 33–35% more dangerous than CO. Hence, we perceive HCN risk 1.35 times as important as CO risk.

Heat exposure from a fire can trigger skin burns, incapacitation, and death in many forms: heat stroke (hyperthermia), body surface burns, and respiratory tract burns [16]. Accordingly, we perceive air temperature CO risk 1.5 times as important as air temperature T risk.

Congestion buildup due to high people density inhibits people movement and hence extends the evacuation time. Because of congestion, the shortest path (in terms of physical distance) is not necessarily the shortest evacuation path. Hence, we perceive people density D risk as being twice as important as the relative physical length factor and 0.5 times as important as air temperature T risk.

Based on the above, it is easy to derive the following approximate values for the weight coefficients α_i

$\alpha_1 = 0.05$; $\alpha_2 = 0.19$; $\alpha_3 = 0.28$; $\alpha_4 = 0.38$; $\alpha_5 = 0.10$

Table 4. Density – risk index mapping

Reported density (person/m^2)	Risk classification	Risk index
D < 4	Low	0
4 ≤**D** <5	Medium	0.5
5 ≤ **D** < 7	High	0.7
D ≥ 7	Very high	1

3.3 Safest route algorithm

Given a weighted graph *G* (*N*, *E*) of the type shown in Fig.3, the objective is to compute the shortest path between each regular node and the closest exit node. To reduce the complexity of the shortest path computation, we decided not to use Floyd-Warshall's algorithm to find the shortest path for every regular source node and exit node, followed by selecting the shortest one. Instead, we will transform the original graph *G* into a new graph *G'*(*N'*,*E'*) by adding a dummy vertex D which is connected to each exit node via a link of weight 0. Fig.4 illustrates the transformation corresponding to the original graph shown in Fig.3.

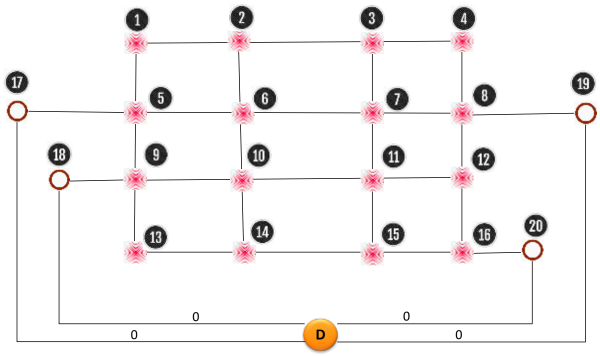

Fig.4. Graph transformation

With this transformation, the problem reduces to finding the shortest path between each regular node (1-16 in Fig.4) and the dummy vertex D. To solve this problem, we use vertex D as source vertex in Dijkstra's algorithm and calculate the shortest distance from D as sources vertex. Note that in our case there was no need to reverse the edges as they are bidirectional.

Inspired by the concept of constrained based routing (CBR) in Multi-Protocol Label Switching (MPLS) Traffic Engineering (TE), we impose minimum safety constraints on each link. This constraint is expressed in terms of avoiding any link that is associated with a risk index of value 1 in the reported T, CO, HCN or human density levels. A link that does not meet the minimum safety constraint is ignored (pruned) prior to applying the CSP algorithm.

There might be cases where pruning can render the graph is unconnected. In this case, when there is no route between a regular node and an exit node, our constrained shortest path (CSP) algorithm will reinstate the pruned link and recomputes the shortest path regardless of the risk state. The CSP algorithm is described below:

CSP (Constrained Shortest Path) Algorithm

Input: Graph G'(*N*', *E*') with weights $W_t(i,j)$

1: Pruning: Ignore links not meeting safety constraints. Check connectivity

2: Set vertex D as source vertex

3: Apply Dijkstra's algorithm

4: Find shortest distance from vertex D as source vertex

5: Output shortest path from each regular node to closest exit node

The above CSP algorithm is a core element (step 3) in the evacuation algorithm, as outlined below:

Evacuation algorithm

Input: Graph G'(*N*', *E*')

1: Collect sensor data from network server

2: Compute edge cost $W_t(i,j)$ for each edge

3: Apply **CSP Algorithm**

4: If (new routes are found) then

Push new directions to smart panels

end if

5: Wait for Δt seconds

6 : Go to **1**

3.4. Evacuation route computation process

When a fire hazard is detected, the central server sends commands to all sensor nodes to increase their reporting frequency above the running frequency of the dynamic evacuation algorithm. This ensures that each time the evacuation algorithm reruns, it receives up-to-date sensor data. The application server has a global view of the topology of the graph. It gathers real-time information from the sensor nodes (via the central server), computes the edge weights $W_t(i,j)$, executes the SCP evacuation algorithm, and communicates with the smart digital panels to activate the proper evacuation arrow directions. As our evacuation algorithm runs every Δt seconds, when congestion builds up along a given pathway, subsequent runs of the CSP algorithm tend to circumvent this link. This indirectly contributes to balancing the flow of evacuees along the corridors, hence contributing to reducing the potential accidents that could occur because of people stumbling along overcrowded corridors.

4. Evaluation of the proposed approach

To validate our proposed evacuation system during a fire blaze emergency, we opted for two simulation tools [17]:

- The *Fire Dynamic Simulator* (FDS) is a computational fluid dynamics (CFD) model of fire-driven fluid flow used here to simulate the spreading of fire inside the exhibition center
- The *Evac* simulator is the evacuation simulation module for Fire Dynamics Simulator (FDS). The software is used to simulate the movement of people in evacuation situations.

We also made use of *Smokeview* (SMV) which is a visualization program that is used to display the output of FDS. Additional information, including source code, can be found at the NIST FDS and Smokeview webpage [18].

4.1. Simulation approach and scenarios

To validate and assess the performance of the proposed approach, we apply two evacuation scenarios for the exhibition center shown in Fig.2: with and without the proposed evacuation routing approach. We vary the initial random distribution of the visitors inside the exhibition, center as well as the fire spreading rate.

4.2. Simulation performance metrics

We have adopted two performance metrics to evaluate the efficiency of the proposed approach:

- The fraction of evacuees that successfully exited the exhibition center (*F*) versus evacuation time (*T*). A higher slope in the F-T curve corresponds to a faster evacuation procedure.
- The fraction of evacuees that could not escape as they get trapped by the spreading fire blaze.

We are currently working on completing the simulation experiments to validate the merits of our approach.

5. Conclusion and future work

In this contribution, we have proposed a dynamic crowd evacuation system for a multi-exit exhibition center. Work is underway to complete the experimental results. Future work can investigate other important considerations in the evacuation planning, such as the width of the exit doors, and the presence of people with special needs. Extending the approach to handle more complex multi-floors scenarios can also be envisaged in future.

Acknowledgements
This research project is financially supported by Zayed University under Research Cluster Grant # R17074.

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