Crowd Guidance for Emergency Fire Evacuation Based on Wireless Sensor Networks*

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Abstract

Emergency building evacuation is important for public safety, and good crowd guidance key for improved occupant survival. In this study, both multiple streaming crowd guidance (MSCG) based on wireless sensor networks and RFID technology were developed. Unlike classical navigation algorithms, the proposed algorithm considers not only how fire propagation affects crowds in stressful conditions but also addresses crowd streaming in/during the evacuation process. In addition, crowd streaming, unexpected accidents, and environment illumination were also considered as factors in developing the algorithm. Moreover, the prediction of potential blockings was conducted by using sensing data from the wireless sensor network.

1 Introduction

Instantaneous and safe movement of people away from threats is the goal of evacuation. Emergency building evacuation plans are important for public safety [1-3] and plans should be developed to ensure the safest and most efficient evacuation. Good crowd guidance is key in improving occupant survival, especially in the case of a fire. Some methods have been proposed for developing escape paths [4-7]. Tseng et al. [5] propose a distributed lower latency and a wireless sensor network with less message overhead for an escape path in building an algorithm. Wang et al. [4] developed a model considering crowd behavior in emergency evacuation. Radio-frequency identification (RFID) is a popular non-contact system for transferring data between tag and reader. There are lots of applications including access management, tracking of goods, etc. Indoor location sensing [8, 9] is an important application of RFID because GPS does not work in buildings. Lee et al. [9] propose a Virtual Signal Location System (VSLS) based on RFID. This can effectively increase the sample quality of the signal as well as the precision. VSLS was adopted as location sensing system in this study.

Wireless sensor networks (WSNs) consist of nodes for monitoring physical environment conditions such as temperature, humidity, light, etc. Applications include area monitoring and air pollution monitoring amongst other. ZigBee is a low cost and low power consumption device supporting point-to-point, point-to-multipoint, and mesh networks. ZigBee devices can serve as wireless routers to relay packets without cables. The way to transfer data between nodes is an essential issue in WSNs. Yu et al. [10] propose a context-aware living environment (CALE) based on a ZigBee sensor network. The updated data can be easily observed and responded to in any situations.

In this paper, we propose a multiple streaming crowd guidance (MSCG) algorithm for emergency fire evacuation. Unlike classical navigation algorithms, fire propagation, crowd streaming, unexpected accidents, and environment level of illumination are considered as factors in the algorithm. An undirected graph was used to represent the floor plan. The vertices and edges represent the spatial block and a path between two blocks, respectively. There are two phases in building the escape path: the macro-phase and micro-phase. In the macro-phase, the escape path was built according the environment factors. In the micro-phase, the crowd behavior was considered to build the multiple streaming escape paths. In order to provide a real-time safety navigation service, WSNs and RFID were used for sensing data and location information.

This paper is organized as follows: In section 2, related work on emergency evacuation and indoor location are given. The proposed navigation algorithm is briefly discussed in section 3. Section 4 presents the scenario of the proposed algorithm and finally, Section 5 gives the conclusion.

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2 Related Works

Some brief reviews of emergency guidance and indoor location sensing methods are given in this section.

Tseng et al. [5] propose building a distributed escape path algorithm based on WSNs. The conditions of the algorithm allow multiple exits and multi-emergency events in the sensing field. According to the simulation results, the algorithm had a lower latency and less message overheads. In order to improve the safety, the shortest path was not the only factor considered in building the escape path. The altitude values were used in the algorithm to describe the danger index. Guiding the altitude from high to low is the key concept in this algorithm. Each node knew where to direct evacuees and could avoid the hazard region. Moreover, the hazard area was an important concept in this study. The proposed algorithm could avoid the potentially affected danger area to improve safety. Wang et al. [4] developed a probabilistic model to characterize analyses how fire propagation affects crowd behavior. The stressful conditions and egress time are important goals factors in this method. The model predicts the potential blockings and provides a foundation for optimizing crowd guidance. The results show that this method evacuated more people and faster. As opposed to the outdoor positioning system (GPS), the precision of indoor location sensing still creates problems. Many methods [8, 9, 11, 12] have been proposed to focus on this issue. Most methods use RFID or WiFi signals to locate positions. In order to improve precision, RFID has become a popular indoor location sensing technology. Lee et al. [9] propose a virtual signal location system (VSLS). VSLS was developed using the same principles and rules of LANDMARC, and the accuracy of positions was improved in comparison with LANDMARC. The main idea was the application of virtual tags using an auto-pilot car to depict signals. In addition, VSLS uses signal strengths from virtual tags and it can save the usage of hardware for the position-sensing up to 2 to 5 times.

3 Multiple streaming Crowd Guidance (MSCG)

The correctness and instantaneousness of environment sensing data and people location are important factors in building the crowd guidance navigation algorithm. Wireless sensor networks (WSNs) are used to transmit sensing data in the environment, such as temperature, humidity, light, CO, CO\textsuperscript{2}, etc. and RFID is used as an indoor location sensing system [9]. In this paper, a multiple streaming crowd guidance (MSCG) algorithm for emergency fire evacuation is proposed. MSCG emphasizes safety and instantaneousness/immediacy instead of the shortest path while building the escape path. Therefore, many factors are considered in MSCG, such as, fire propagation, crowd streaming, unexpected accident, and level of illumination. An undirected vertex weight graph is used to represent the floor plan. Vertices and edges are representing the space block and path between blocks, respectively. With the comprehensive consideration of above factors, a danger index (DI) is calculated and applied on each vertex. The higher the value of DI the more danger. Therefore, navigation is done by following the decreasing DI. MSCG has a pre-process stage, a sensing and event trigger stage, and an emergency evacuation stage. In the pre-process stage, the floor plan was properly converted into an undirected graph to represent indoor space, and the distance between each vertex and exit was also calculated at/during this stage. In the sensing stage, environmental data are continuously transmitted from sensors to sensor controller, and the location of people is continuously calculated and identified. Moreover, triggering the fire event is also determined during this stage. Finally, in the emergency evacuation stage, following procedures are continuously processed in time: (1) calculating DI, (2) adding illumination affect to DI, (3) deadlock detection, (4) deadlock removal, (5) building escape path, and (6) stagnation detection.

3.1 Pre-processing Stage

1) Convert Floor Plan into a Graph

\[ G = (V, E) \] is an undirected graph used to represent the floor plan. Let \( V = (v_1, ..., v_n) \) be the spatial block and \( E = (e_1, ..., e_m) \) be the path between two blocks if the existing path. The \( \deg(v_i) \) is the number of edges connected to \( v_i \), and it also shows the number of escape paths to be blocked \( v_i \). The value of \( \text{isExit}(v_i) \) is true if \( v_i \) is the exit block, otherwise its value is false.

2) Distance between the Block and Exit

The distance between each block and exit block is calculated according to the shortest hops between them. The value of \( \text{distToExit}(v_i) \) is determined as follows:

Let \( \text{nonExitVertex} \) be the set of vertices where \( \text{isExit}(v_i) \) is false for \( i = 1, ..., n \) and \( \text{exitVertex} \) be the set of vertices where \( \text{isExit}(v_i) \) is true for \( i = 1, ..., n \). The \( \text{distToExit}(v_i) = \min(|\text{shortestPath}(v_i, v_j)|) \) for each vertex \( v_j \) in \( \text{exitVertex} \) set.

3.2 Sensing Stage

Sensors are continuously transmitting the sensing data to the controller including environment sensing data and people location data. The controller detects the fire event according to the following conditions.

Let \( \text{temp}(v_i) \) be the sensing temperature of \( v_i \). The stage will transfer from “sensing stage” to “emergency evacuation stage” if there is a \( \text{temp}(v_i) \geq 50 \text{°C} \) for 5 seconds where \( i = 1, ..., n \).

3.4 Emergency Evacuation Stage

There are two phases while building the escape path: macro- and micro-phases. In macro-phases, environment conditions are main affection factors including fire event influence index, crowd ratio, and illumination. Six procedures are designed in
In this phase, in the micro-phase, a multiple streaming escape path building method according to multiple exit paths is proposed. Some notations are described as follows:

- \( CR_i \): crowd ratio of \( v_i \), \( CR_i = \frac{\text{number of people in } v_i}{\text{capacity of } v_i} \) \%
- \( HC_{i,j} \): hop counts from \( v_i \) to \( v_j \).
- \( FEII_{i} \): fire event influence index of \( v_i \). For the fire event vertex (\( v_i \)), the value is 110. Otherwise, the values are 95, 85, 75 if the values of \( HC_{i,j} \) are 1, 2, 3.
- \( L_i \): illumination value of \( v_i \) in lux.
- \( ST_i \): stagnation time of \( v_i \) in seconds. \( ST_i \) is the time period in seconds while \( CR_i \) does not change and \( CR_i \neq 0 \).
- \( stagTime \): the threshold of stagnation time period.

1) Macro-phase

In this phase, six procedures are processed to calculate the danger index (\( DI \)) for each vertex. First of all, \( DI \) considers the crowd density and the fire event influence.

\[
DI_i = \begin{cases} 
-5, & \text{if } v_i \text{ is the exit vertex} \\
\max( CR_i, FEII_i ), & \text{if } \max( CR_i, FEII_i ) \geq 90 \\
\max( CR_i, FEII_i ) \times 0.8 + \min( CR_i, FEII_i ) \times 0.2, & \text{else}
\end{cases}
\]

Light is an important element in the emergency escape path, therefore, the \( DI \) is increased if illumination is too low.

\[
DI_i = \begin{cases} 
DI_i + 10, & \text{if } L_i \leq 10 \\
DI_i, & \text{else}
\end{cases}
\]

The main concept of escape path building is navigating people from higher a \( DI \) area to a lower \( DI \) area. Therefore, deadlock can be avoided. For \( v_i \), all of the values of \( DI_j > DI_i \), where \( HC_{i,j} = 1 \). In order to remove the deadlock, the value of vertex is increased iteratively until there is no deadlock vertex anymore.

while \( v_i \) is a deadlock point: \( DI_i = DI_i + 10 \) for \( i = 1, \ldots, n \)

In order to avoid some unexpected situations, stagnation detection is proposed. If people do not move from one spatial block to another in a given time period, the \( DI \) will be increased.

\[
DI_i = 100 \text{ if } ST_i \geq stagTime
\]

2) Micro-phase

In the macro-phase, the escape path was built according to the environmental conditions without considering the number of people and the number of exits for a given vertex. In the micro-phase, the people were navigated according to the distance and capacity of exits (e.g., door size). Figure 1 illustrates an example of grouping results.

Figure 1. Example of grouping results.

4 Scenario

In order to verify and to clearly describe the MSCG algorithm, a scenario is given in this section. Figure 2 is an example of the floor plan. There are 10 rooms and 2 exits connected by corridor.

Figure 2. Example of floor plan for scenario.

4.1 Pre-processing Stage

The floor plan of the building is transferred to a graph during this stage, and the distance between each block and exit is also calculated. Figure 3 is a graph with 20 vertices and 16 edges, the solid circle vertices and dash circle vertices represent the rooms and divided corridor, respectively. The number of each vertex represents the hop counts to the nearest exit vertex.
4.2 Sensing Stage

MSCG uses WSNs to collect the environment conditions including temperature, humidity, light, etc. The indoor positions of people are determined by RFID. Figure 4 shows the detected fire event (dotted circle vertex).

4.3 Emergency Evacuation Stage

An example of crowd ratio (CR) is given in Figure 5, and Figure 6 illustrates the fire event influence index (FEII). According to the formulation of the danger index (DI), we had Figure 7. The main concept of navigation is directing people from high DI into low DI. However, some vertices are in deadlock (vertex with outlined diamond background in Figure 8). Therefore, the deadlock removal procedure is processed to resolve this (Figure 8). Figure 9 illustrates an example of an escape path built according to the MSCG algorithm. If the stagnation is detected (vertex with outlined diamond background in Figure 10), the DI of the stagnation vertex is increased and the entire procedure is run again Figure 11.
5 Conclusions

Building effective crowd guidance is important for emergency evacuation. A good navigation algorithm is key to improve occupant survival. In this paper, a multiple streaming crowd guidance (MSCG) algorithm for emergency fire evacuation is proposed. The main concept of MSCG is safety and instantaneousness, therefore, many influence factors and crowd behaviors have been considered. Moreover, MSCG also uses the people location information to detect unexpected accidents and re-route the escape path. In the simulation, ZigBee and RFID were used to transmit the sensing data and identify people location information, respectively, to verify the MSCG. In future, the integration of mobile devices could provide a safer and more efficient navigation service.

References


