Decentralized Evacuation System Based on Occupants Distribution and Building Information

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ABSTRACT

Effective evacuation is critical for safety of occupants. The exiting evacuation systems lack flexibility and don't consider the distribution of occupants. It is possible to direct occupants to danger areas or cause congestion in certain areas. In this paper, a decentralized evacuation system is proposed to compute the safest path in real time. The system is composed of fire detection sensors, zone controllers, elevator sensors, human tracking and monitoring systems and dynamic egress signs. All devices are placed at the predetermined locations based on integrated design of the building. The entire building is divided into many basic zones which are operating quite independently, and global information is communicated to neighboring zones and consequently to entire network by zone controllers. The system acts in decentralized fashion. The elevator and dynamic factors are considered in guidance system. Simulations are performed to determine the advantage of the system.

Keywords

Evacuation guidance, decentralized system, sensor and network, decision making support system

INTRODUCTION

The public and residential buildings are becoming larger and more complex due to interaction between building structure and human movement. As we know, accidents or a fire in large building may cause severe casualties and property loss. Once a fire occurs in a building, occupants may get into panic. It is vital to provide occupants appropriate information and guide them to the safe place effectively. Therefore there is a need to develop a reliable system to guide occupants to evacuate effectively. Traditional evacuation systems deployed in buildings are static and lack of flexibility. For complex situation it is possible to guide occupants to danger areas. Traditional evacuation systems also don't consider the distribution of occupants. This may cause congestion at certain areas or at exits. Li *et al* (Ii, Chang, Mu and Zhao, 2003; Ii, Mu, Chang and Yan, 2005) exploited the evacuation systems which can monitor the fire in real time and gave guidance to occupants by voice, light and direction board, but they didn't consider the distribution of occupants. Pu *et al* (Pu and Zlatanova, 2005) developed a new evacuation system based on 3D building model and navigation devices to give evacuation instruction to occupants, the approach took definite factors into account and the system provided occupant dynamic evacuation route with mobile devices. However, it is difficult to obtain the 3D structure of building correctly, and the processor has to deal with a great deal of information. In general, such evacuation systems are implemented in a centralized fashion. Meanwhile, with the development of wireless, networking and sensors, new methods are added to the evacuation technologies (Fischer and Gellersen, 2009; Lorincz, Malan, Fulford-Jones, Nawoj, Clavel, Shnayder, Mainland, Welsh, and Moulton, 2004), the evacuation systems can find safe paths based on real-time information. Tseng *et al* (Tseng, Pan and Tsai, 2006; Pan, Tsai and Tseng, 2006) proposed a distributed navigation algorithm, and extended it to 3D environment. Sensors were classified as normal sensors, exit sensors, and stair sensors, and were used to monitor the environment and establish escape paths for occupants. Filippoupolitis *et al* (Filippoupolitis and Gelenbe, 2009; Gelenbe and Wu, 2012) also developed an evacuation system composed of a network of decision nodes and sensor nodes, all sensors were deployed in predetermined locations in the building to form a distributed network, so as to compute the safest evacuation path. The evacuation system using sensors are all decentralized to some degree, which brings new breakthrough for intelligent building. However, algorithms mentioned here contributed to a path escaping from the hazardous region but not considered the distribution of occupants. It is possible to result in jam in certain local zones.

In addition, elevators as exits in fire are proven available in practice and are studied by many researchers. The researches can be classified into three categories. The first one focused on elevator evacuation algorithms, for example, Klote and Siikonen *et al* (Klote, 1993; Siikonen and Sorsa, 2011) presented methods to calculate evacuation time by elevators in emergency. The second one contributed to group elevator scheduling, for example, Narendra *et al* (Narendra, Gowthami and Jayasree, 2013) introduced different operation mode including emergency mode. The last one was about new elevator evacuation system. For example, Shi *et al* (Shi, Goto, Zhu, and Chen, 2013) proposed a type emergency elevator system which could detect and predict hazards in emergency evacuation.

This paper develops a decentralized fire evacuation system and proposes a new decentralized algorithm following the idea of taking elevator as exits. The system is more intelligent and the algorithm considers more dynamic factors, such as distribution of occupants and fire location. A simulation experiment is conducted to estimate the algorithm and show how the proposed system works.

DECENTRALIZED EVACUATION SYSTEM

The biggest difference between decentralized and centralized evacuation system is that the decentralized one does not depend on global information of building but mainly on local information. The centralized system is usually vertically integrated. If a part of the system is damaged by fire, the entire system may disfunction. However, the decentralized system organized sensor network is horizontal. It is robust and its decision process is quick. The decentralized system presents more advantages compared to the centralized control system in complex building through advanced IT technologies.

To build up a decentralized evacuation system, the first step is to build partition. The building should be divided into several basic or functional zones which can operate independently. Global information is communicated between neighbor zones and spreads to entire network by zone controllers.

Zones division

Before zone division we need to know the layout of building. Some rules should be followed to divide zones: (1) each zone should be continuous, (2) none of zones are overlapped, (3) avoid many neighbors for one zone, (4) the zone area is between $30m^2$ to $50m^2$.

Each zone is equipped with data acquisition equipment, data processing equipment and 3D dynamic egress signs. Data acquisition equipment includes sensors, videos, RFID and access control systems of building. Data processing equipment mainly refer to zone controller. Fire sensors in zones monitor the fire situation in real time. Videos, RFID and access control systems are used for identifying the distribution of occupants. The zone controller acts to process information gathered from local sensors and their neighbors. The zone controller in each zone only communicates to its neighbors and local sensors. 3D dynamic egress signs are used to provide directions for evacuation.

In zone division, each elevator is considered as one zone. It is different from other zones because the elevator car is moving, the elevator zone could not communicate with some floor directly all time. To solve the problem, a new idea is developed inspired by a research of Shi *et al* (Shi et al., 2013). Figure 1 shows the architecture of elevator zone. One zone controller is deployed on each floor. Sensors and videos are deployed to detect temperature, gas and number of occupants in elevator car. Elevator control system communicates with zone controllers in real time. Elevator sensors communicate with different zone controllers along with movement of elevator car. Once fire occurs at certain floor, the zone controller at that floor will communicate information to its neighbors. Then the neighbors will transmit the information to their neighbors, consequently the elevator control system knows the information. Similarly, situation in elevator car is known by all zone controllers and elevator control system. After that, the elevator turns to evacuation mode and works as an exit for the evacuated floor but not for other floors.

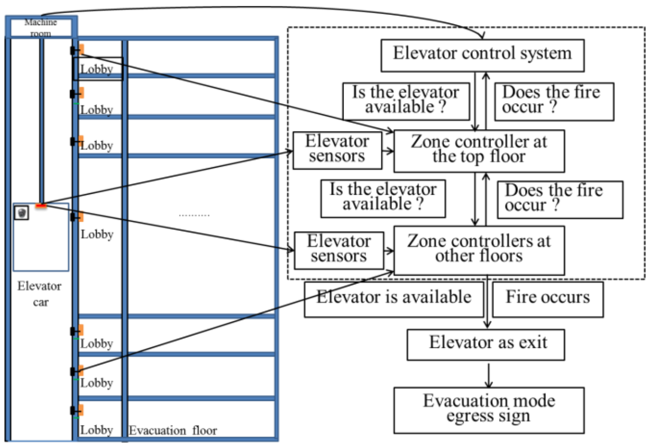

Figure 1. The Architecture of Elevator Zone

Information transmission network

In a decentralized system, one zone controller communicates only with its neighbors. To establish information transmission network is to find all zone's neighbors. Two communication rules are applied based on spatial relationship and spatial connectivity. The first is that all zones adjacent to certain zone on the space are considered as its neighbors. The second is that two zones are considered as neighbors if they are adjacent on space and able to form continuous space. For decentralized evacuation system, the second rule is suitable. Two adjacent zones are considered as neighbors when doors exist between them.

Decentralized algorithm

The evacuation algorithm proposed in this study devotes to find a safest path to exits for occupants. It is executed by each zone controller. The basic idea of the algorithm is as follows: a zone takes information from its neighbors constantly and selects the most suitable neighbor to exits as the evacuation direction. As mentioned before, the building is divided into many basic zones. All zones can be classified as normal zones, stair zones and elevator zones. Assume zone i and zone j are discretionary two zones in the network, and they are neighborhood, zone j is guided to zone i, the evacuation time for zone j (T_j) equals to the evacuation time for zone i (T_i) plus the evacuation time for occupants in zone j from zone j to zone i (T_{ij}), as expressed in Equation (1).

$$T_j = T_i + T_{ij} \tag{1}$$

T_{ij} is different for different conditions: (1) when zone i and zone j both are normal zones, T_{ij} is decided by the number of occupants in zone j (x_j), geometrical distance between zone i and zone j (l_{ij}) and the evacuation velocity of occupants (v), as in Equation (2). (2) when zone i is a stair zone and zone j is a normal zone, T_{ij} is decided by the number of occupants in zone j (x_j), geometrical distance between zone i and zone j (l_i), the evacuation velocity of occupants (v) and the flow rate entering the stair (f_s), as in Equation (3). (3) when zone i is an elevator zone, zone j is a normal zone, T_{ije} is decided by the number of occupants in zone j (x_j), geometrical distance between zone i and zone j (l_{ij}), the evacuation velocity of occupants (v), the flow rate entering the elevator (f_e),the elevator capacity (c) and the waiting time for the elevator for occupants in zone j (w), (w) is depends on the dispatching algorithm of elevators which is not given here, as in Equation (4).

$$T_{ij} = f(x_j, l_{ij}, v) \quad (2)$$

$$T_{ij} = f(x_j, l_{ij}, v, f_s) \quad (3)$$

$$T_{ij} = f(x_j, l_{ij}, v, f_e, c, w) \quad (4)$$

We take figure 2example for to illustrate the algorithm. As showed in figure 2, zone 1 is considered as the elevator zone and zone 4 is considered as the stair zone, other zones will choose them as the exit. Assume two adjacent zones become neighbors each other and the geometrical distance between them is all equal, which equals to 1. There are same occupants in zones except zone 8, zone 8 have more occupants than others. The fire occurs in zone 11. L means the total geometrical distances from the local zone to the exit it choose. LN means the total geometrical distances from the local zone to the other exit it doesn't choose. The solid arrows stand for the evacuation direction of different zones based on the algorithm. For example, zone 14 is elected by zone 15 as evacuation direction. The evacuation time for zone 15 is calculated using Equation (1) and Equation (2), the evacuation time for zone 5 is calculated using Equation (1) and Equation (4). For node 11 and node 15, they choose the elevator as the exit even though the distance to stair for them is closer (the dotted arrows exist if they choose the stair), become it takes less time using elevator compared to the stair, for zone 7, it choose zone 3 become zone 8 have more occupants then zone 3, so it can take less time to evacuate for zone 7.

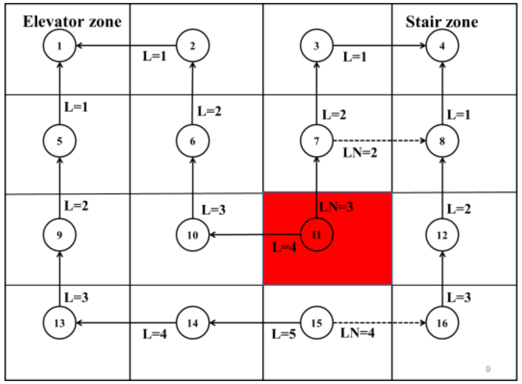

Figure 2. An Example of The Algorithm

Description of decentralized evacuation system

The decentralized algorithm and various devices support the system implementation. Figure 3 shows the overall architecture of the system. In a decentralized evacuation system, the entire building is divided into many basic zones. Fire detection sensors, zone controllers, human tracking and monitoring systems and dynamic egress signs are deployed most in each zone. Sensors monitor the temperature, gas, smoke and fire situation in real time. Human tracking and monitoring system including videos, RFID and access control system of building collect the information of occupants and ensures the distribution of occupants in real time. The control system of elevator, elevator sensors and videos tell the system if the elevator and stairs are available. Each zone controller processes information and communicates information with local sensors and its neighbors. Once fire is detected, the local zone controller communicates the information to its neighbors. The neighbors then spread the information to their neighbors. Consequently the whole network is informed the message. When the zone at exits receives fire information, it initiates the decentralized algorithm. A safest evacuation path based on the algorithm will be calculated by the whole network. 3D egress sign in each zone presents the path and provides the direction to guide evacuees to evacuate. As all information is monitored and gathered in real time, the evacuation instruction can be updated and adapted to new situation.

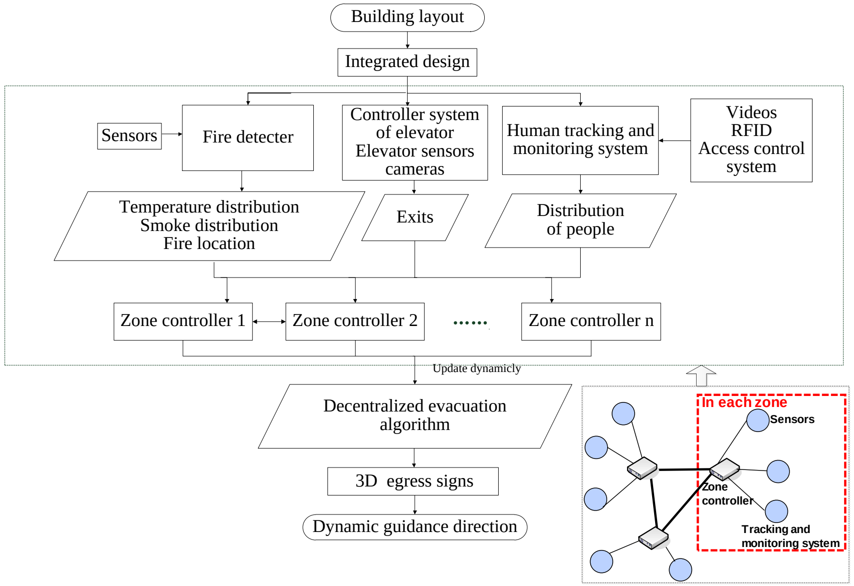

Figure 3. Overall Architecture of Decentralized Evacuation System

SIMULATION EXPERIMENT

The decentralized evacuation system is installed at the tenth floor in a building. Simulations by MATLAB to imitate the real building with all devices performed to evaluate the performance of the algorithm and the system. There are two staircases and two elevators in the building, and the elevator room is connected with one of the stairs. In the simulation experiment, only one elevator and two stairs can be used as exits. One elevator car can afford 13 occupants at most. Figure 4 shows the architecture of building, its zone division and corresponding information transmission network. The building is divided into 16 zones, zone 9 and zone 16 are stair zones and zone 11 is the elevator zone. Fire occurs in zone 13. Blue ligatures between two nodes constitute the information transmission network based on the spatial connectivity. All occupants should be evacuated to the first floor. Table 1 is the number of occupants in each zone. Moreover, the geometrical distances between neighborhood zones are also given, which the red fonts show.

Node	1	2	3	4	5	6	7	8
Number of occupants in zone	2	1	2	5	6	1	10	14
Node	9	10	11	12	13	14	15	16
Number of occupants in zone	1	3	0	12	18	20	1	0

Table 1. Number of Occupants in Each Zone

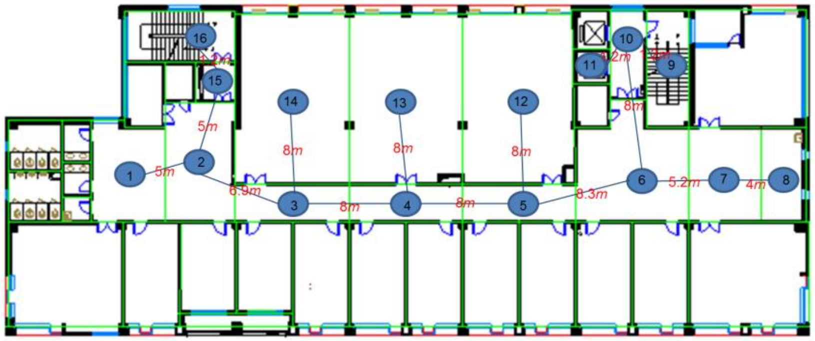

Figure 4. Architecture of the building and its integrated design

Table 2 shows the results of evacuation time for each zone and the number of occupants evacuated to various exits. Table 2 shows that 26 occupants in six zones choose the left stair, it takes 129s to evacuate all occupants, 32 occupants in zone 8 and zone 13 choose the right stair, the max evacuated time is 155.5s; 38 occupants in eight zones choose the elevator the max evacuated time is 122s. Figure 5 shows the percentage of occupants choosing various exits. It indicates the decentralized evacuation system can provide a safest path and guide occupants to evacuate effectively. It also has good performance in balancing the number of occupants to different exits. More occupants are guided to choose elevator and this takes less time than stairs as exit.

Node	1	2	3	4	5	6	7	8
Time(s)	106.5	99.5	101.5	108	72	60	80	160
Exit selected	left stair				elevator			right stair
Number of occupants for exits	5				22			14
Node	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Time(s)	1	3	0	12	18	20	1	0
Exit selected	elevator				right stair		left stair	
Number of occupants for exits	16				18		21	

Table 2. Result of Evacuation

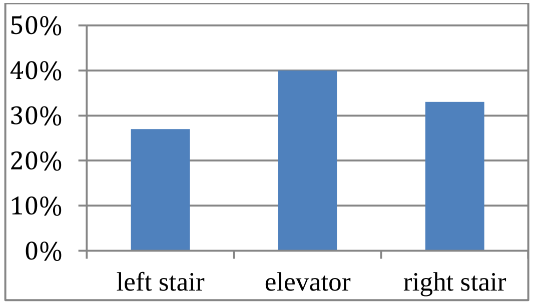

Figure 5. Percentage of Occupants Choosing Various Exits

Figure 6 shows the evacuation path according to the initial information, egress sign in each zone gives direction to occupants to help them make decisions to its some neighborhood zone, and finally find most suitable exits. The red arrows stand for the direction that each egress sign gives.

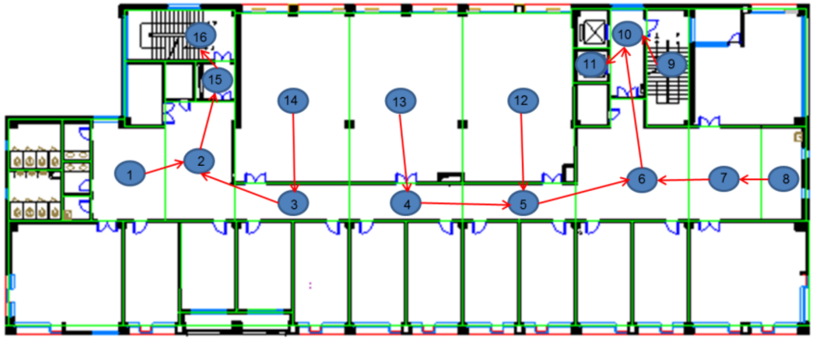

Figure 6. Evacuation Path

CONCLUSION

This paper presents a decentralized evacuation system which unifies fire monitoring systems, security systems and elevator systems. An algorithm is also developed by taking dynamic factors, such as the fire location, the distribution of occupants in zones and the elevator factors, into account. The algorithm and evacuation system are designed as decentralized style, which performs well in robustness and flexibility. It is also demonstrated that the system can provide effective guidance and decisions for occupants. However, occupants behaviors are not considered in the algorithm, for example, we think occupants wait for the elevator in order, but it is not facts sometime. Besides the simulation is just based on one-story building structure, simulations and experiments on multi-story buildings will be made in our future work.

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