

Fire Hazard Location Algorithm for Large Place Based on Wireless Sensor Network

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Abstract—Fire hazard monitoring and evacuation for building environments is a novel application area for the deployment of wireless sensor networks. In large place such as a marketplace, it is crucial for firefighters to know the fire hazard situation, and decide on how to best tackle the disaster. Fire sensors in the traditional fire hazard monitoring system are isolated in large place, and it results in failure to remain aware of current overall fire conditions. To improve the assessment accuracy of fire situation, a novel wireless sensor network based algorithm is proposed in this paper to detect and localize the origin of fire hazard in large place. Fuzzy artificial neural network is trained by fire signal from the wireless sensor nodes, then determine whether the fire hazard occurred and estimate its situation. The smoke and temperature diffusion models in limited space are adopted to localize the origin of fire hazard. Theory analysis and experimental results show that this fire detection and localization algorithm could more accurately assess fire hazard situation in large place, which is helpful for firefighters to take measures to exterminate fire hazard.

Index Terms—Fire hazard detection, Fire origin localization, Wireless sensor network, Fuzzy artificial neural network

I. INTRODUCTION

Fire hazard is an involved process, and is costly and dangerous because it causes extensive damage both to property and human life. It may cause a fire hazard when people don't shut off the gas equipment and high-power electrical equipment promptly in day-to-day activities. What's more, fire hazard, which happens in crowded public places, tends to cause greater casualties and property losses. Detecting and localizing the fire hazard timely and accurately is an effective way to prevent or mitigate lose.

In traditional fire detection system, fire sensors sensing smoke and temperature are connected by cables, and these signals are transmitted to and processed in a powerful computer, where the decision about fire hazard occurred or not is made. In the existed buildings or some

large places, these installed cables would damage the functionality and artistry of the buildings to some extent. Due to the high cost and costly maintenance, the wired network is unsuitable and inconvenient choice for fire hazard detection in large space.

Wireless sensor networks (WSN) have been attracting many research efforts during the past few years and they have been developed rapidly. Sensor networks, usually composed of a few sinks and a large quantity of inexpensive and small sensor nodes, have been deployed in a variety of applications[1], such as habitat monitoring[2], forest fire detection[3], structural health monitoring[4] etc. Wireless communications offers new possibilities in the field of fire detection [5-7]. A wireless fire detection system presents new features and advantages in front of the traditional detection systems, such as the absence of cables, connectors and infrastructure, obtaining an easy, economic and quick installation, offering the possibility to change the number of detectors and their position in an extremely simple way. This facility acquires a special interest when the volume to cover varies with certain frequency such as occurs in big cars, museums, exhibition areas, pavilions and so on.

Although fire hazard takes place in bursts, there are certain regularities once it occurred in shopping malls and other large places, for example, rising concentration of smoke, gas and carbon monoxide and twinkling flame [8]. It is very important for fire hazard detection in large place to integrate these signature signals, which could be sensed by multi-sensor terminals. Only one device with multiple fire sensors is suitable in family, office and other small space, however, there are many drawbacks when it is applied in large places. Firstly, it is difficult for one or a few of isolated detection nodes to cover whole area [9]. Secondly, it is also hard to accurately describe the fire information with temporal variability by a single mathematical model. Thirdly, the dense calculation often require higher-performance processor, but low-speed chips like single-chip microcomputers are used in traditional fire detection, and it could not achieve perfect

performance of fire detection. Finally, the firefighters often subjectively estimate the situation of fire hazard and make fire-extinguishing decision and it could lead to missing the best opportunity to rescue life and property [10].

This paper adopts the ZigBee wireless sensor network to set up fire hazard monitoring system for information collection, and proposes a fire hazard detection and localization algorithm in large place by means of fusing fire information from multi-nodes and deducing fire source localization and fire situation. Theory analysis and experimental results show that the fire hazard detection and location algorithm could improve the performance of fire hazard detection, and can speed up fire warning to reduce property losses.

II. TOPOLOGY STRUCTURE OF FIRE HAZARD MONITORING SYSTEM IN LARGE PLACE

Since single node has disadvantage of small coverage and poor robustness, the wireless sensor networks with multi-nodes is adopted to monitor fire hazard in this paper. This wireless networks can not only extend its monitoring coverage area and know overall fire situation in large place, but also prevent false alarm from a single node due to human misoperation, and improve warning accuracy [11-15].

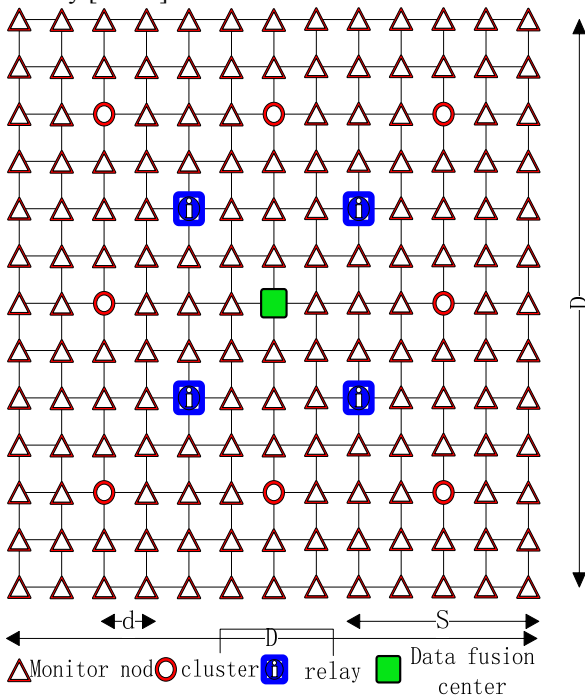


Fig. 1 Topology diagram of fire hazard detection in large place

Fig.1 is the topology diagram of fire hazard detection and location system for large place based on wireless network [16]. Considering in a large place with area of $D * D$ square meters, a fire monitoring node is placed per d meters. There is a cluster head node in each sub-network of area within a $S * S$ square meters. Firstly, the cluster head recognizes that which subnet node belongs to him via the short address of ZigBee network, and fuses the data from each subnet, and then

sends aggregated data to the relay node. Secondly, relay node transmits the data from each subnet to the data fusion center, where the decision whether a fire hazard occurred is made, and the fire hazard location and situation in large places are assessed [16].

III. FIRE DETECTION ALGORITHM FOR SINGLE-NODE

Fire occurred in large spaces is both random and deterministic. The randomness means the unpredictability about the time when the fire broke out, the size of fire, and the fire source location. The determinacy means that there are phenomena happening when fire hazard breaks out, such as, rising concentration of smoke, gas and carbon monoxide, twinkling flame and rising temperature. If the phenomena could be sensed by the corresponding sensors in real time, the fire hazard detection performance would be significantly improved by means of extracting the potential and stable characteristics and reasoning the variation regularity of fire propagation. However, the measuring data may be affected by background noise. In this case, the fire monitoring system should be able to intelligently cope with various environmental parameters, thereby reducing the probability of false alarm. Due to the advantages of artificial neural networks with inaccurate information parameters, it is reasonable to apply it to process the data captured by the wireless sensors for fire monitoring system [17-19].

Back Propagation (BP) neural network adopted in this paper is divided into three layers shown in Fig.2 [20][21]. The first layer is the input layer, consisting of sensor data input nodes; the second layer is the hidden layer; and the third layer is the output layer. I_1, I_2 and I_3 are temperature, smoke concentration and carbon monoxide concentration, respectively, and they are normalized in the range of $[0, 1]$. To filter the noise generated in sensor, they are preprocessed via a low pass filter. The three outputs O_1, O_2 and O_3 represent naked flames probability, smoldering fires probability and no fire probability, respectively. The range of the three outputs are also limited in $[0,1]$. There are five nodes in the hidden layer according to the experience and simulation results [22]. BP neural network algorithm learns the weight factors by minimizing the total mean square error [23], the weight coefficients between the input layer and the hidden layer are w_{ij} , and that between the hidden layer and output layer are v_{jk} .

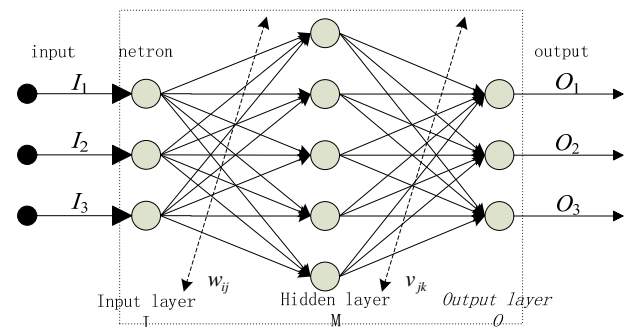


Fig.2 Model of BP neural network

In Fig. 2, the weighted input of the j th node in the hidden layer is

$$T_1(j) = \sum_{i=1}^n w_{ij} I_i \quad (i=1,2,3) \quad (1)$$

The activation function in hidden layer adopts the continuous and differentiable hyperbolic tangent S-type function, and it is

$$f(x) = \frac{1}{1 + \exp(-x)} \quad (2)$$

Putting $T(j)$ into activation function, the output of the hidden layer would be

$$M_j = \frac{1}{1 + \exp(-T_1(j) + \theta_1)} \quad (j=1,2,3,4,5) \quad (3)$$

Similarly, the weighted input of the output layer is

$$T_2(k) = \sum_{j=1}^n v_{jk} M_j \quad (j=1,2,3,4,5) \quad (4)$$

Therefore, the output of the output layer adopts the same S-type function to represent the probability of fire hazard.

$$O_k = \frac{1}{1 + \exp(-T_2(k) + \theta_2)} \quad (k=1,2,3) \quad (5)$$

where θ_1 and θ_2 represent the threshold value, and they are updated constantly according to the criteria of minimal mean square error in the gradient descent learning algorithm.

In view of the limited amount of actual fire data, which couldn't represent all conditions of fire hazards, and limited generalization ability of neural network, there would be boundedness only using the output of the neural network to decide the fire situation. Therefore, a fuzzy reasoning decision-making layer (IF-THEN) is implemented for fire warning judgment after the neural network, and it is contributed to achieve the final fire verdict. If it cannot judge the result, the system will reacquire data again after delaying t seconds to determine whether the fire occurred or not.

Let the output variables of neural network, namely, naked flames probability $P1$, the smoldering fires probability $P2$ and no fire probability $P3$ as the input of fuzzy logic judgment, the judgment rules are as follows:

$$STATE = \begin{cases} \text{naked flame} & P1 \geq TH1 \\ \text{smolder flame} & P1 < TH1 \ \& \ P2 \geq TH2 \\ \text{no fire} & P1 < TH1 \ \& \ P2 < TH2 \ \& \ P3 \geq TH3 \\ \text{delay } Ts \text{ to detect} & P1 < TH1 \ \& \ P2 < TH2 \ \& \ P3 < TH3 \end{cases} \quad (6)$$

IV FIRE CONFIRMATION AND FIRE SOURCE LOCALIZATION

As discussion above, global naked fire probability, smoldering fires probability, and no fire probability can be depicted out by taking advantages of the sensor data from the respective nodes of WSN for large places as shown in Fig.1. By judging the account and location of adjacent alarm nodes, the system can further determine the current coverage of fire hazard and fire situation. it

would be conducive for the firefighters to make the most accurate fire-fighting decision at the first time and to reduce the loss of life and property caused by the fire.

A. Fire source Localization based on Smoke Diffusion Field

In the early stage of fire, due to incomplete combustion of the combustible material, the fire is not very strong with billowing smoke. At this stage, the temperature of the environment is not yet fully rising to the maximum, so the smoke diffusion model can be used to get the information of ignition position at the first time [24]. There is regularity of the smoke diffusion under static wind state, and the diffusion model is shown in Fig.3. The concentration of smoke is higher at the location of the fire source, and it monotonously decreases with increasing distance apart from the origin of fire.

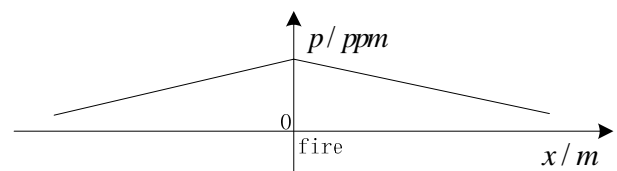


Fig.3 Diffusion model of fire gas

In this paper, we take the environment shown in Fig.4 as the example to elaborate the fire source localization algorithm. Three smart sensor nodes are placed in the room, where the nodes named 1, 2 and 3 are placed at the inner wall of the outer side, and the fire source is placed on the floor. According to the smoke diffusion model, let the spread speed of the smoke be v (ppm/ m), and the smoke concentrations p_i of the valid monitoring nodes names 1, 2 and 3, the distance from the node to the source of fire could be calculated, $r_i = p_i / v$.

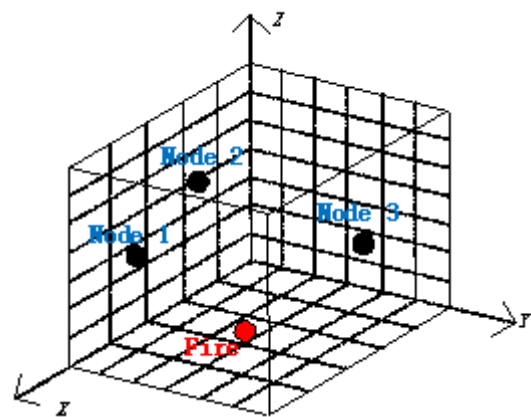


Fig.4 Indoor fire source localization model

The trilateral location method is adopted in this paper to locate the fire hazard. If the coordinates (x_1, y_1, z_1) , (x_2, y_2, z_2) and (x_3, y_3, z_3) of the reference nodes 1, 2 and 3 are known, the location (x, y, z) of the fire source could be obtained by solving the following equations.

$$\begin{cases} (x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2 = r_1^2 \\ (x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2 = r_2^2 \\ (x-x_3)^2 + (y-y_3)^2 + (z-z_3)^2 = r_3^2 \end{cases} \quad (7)$$

$$o = (o_g + o_i) / 2 \quad (10)$$

V. EXPERIMENTS AND ANALYSIS

A. Fire Detection Probability of Single-node

By solving the above equations, the coordinates of the fire source can be derived $o_g = (x_0, y_0, z_0)$. If there are more than three nodes receiving the smoke information about fire hazard, the fire position based on smoke diffusion field would be more accurate.

By training the samples provided by European standard fire experiments for 30,000 times, the weights coefficients w_{ij} and v_{jk} of neural network would be gotten, and they are listed in Table. I and Table. II, respectively.

B. Fire source Localization based on Gas Temperature Field

In the mid-late period of the fire hazard, due to complete combustion of combustible materials, the smoke concentration is lower than before and the ambient temperature rises rapidly. In this situation, the method based on smoke diffusion model can not accurately locate the fire hazard source, and the gas temperature field model is available to further determine the location of the fire source [25]. When the fire hazard broke out, the three-dimensional unstable temperature field model can be used to describe the indoor gas temperature field. The temperature field not only changes in the space, but also changes over time, and the propagation process of the temperature field can be described by a three-dimensional heat conduction partial differential equation, which is represented as the following formula.

$$\frac{\partial T}{\partial t} = \frac{\lambda}{c\rho} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = a \nabla^2 T \quad (8)$$

By setting the initial and boundary conditions, the indoor fire temperature propagation model is described using spatio-temporal field $T = f(x, y, z, t)$.

At the same time t_0 , if the fire temperature sensed by the reference nodes 1, 2 and 3 are T_1 , T_2 and T_3 , respectively, the location (x, y, z) of the fire source could be obtained by solving the following temperature propagation equations.

$$\begin{cases} T_1 = f(x_1 - x, y_1 - y, z_1 - z, t_0) \\ T_2 = f(x_2 - x, y_2 - y, z_2 - z, t_0) \\ T_3 = f(x_3 - x, y_3 - y, z_3 - z, t_0) \end{cases} \quad (9)$$

Solving the above equations, the location coordinate of the fire source is obtained: $o_t = (x_0, y_0, z_0)$. If there are more than three nodes receiving the gas temperature about fire hazard, the fire position based on gas temperature field would be more accurate.

In order to reduce the detection error further, the system can jointly take use of fire smoke diffusion model and the temperature diffusion model to get an approximate solution of two fire location, so that more accurate location of fire source can be obtained as the average of two values.

TABLE I
WEIGHT COEFFICIENTS w_{ij} BETWEEN INPUT AND HIDDEN LAYERS

	w_{1j}	w_{2j}	w_{3j}	w_{4j}	w_{5j}
temperature	-2.5258	-3.8553	-1.3059	2.1085	3.5102
smoke	-2.6000	0.6174	-1.0543	-4.5110	-1.4072
co	-2.2886	2.8149	-5.7332	0.2795	-2.9719

TABLE II
WEIGHT COEFFICIENTS v_{jk} BETWEEN HIDDEN AND OUTPUT LAYERS

	Fire probability	Smoldering probability	No fire probability
v_{1k}	0.3230	-0.9932	0.2068
v_{2k}	-0.6052	1.0205	-0.3100
v_{3k}	-2.2150	-0.8814	3.9156
v_{4k}	-1.0485	1.2502	-0.0672
v_{5k}	2.4957	-2.4530	-0.9444

Taking advantage of neural network, the test samples are divided into two parts: one part is used for training, and the other for testing. The experiment results shown in Fig.5 indicate that the fire detection algorithm based on neural network gets good performance for the error between the actual data and the estimated data is very small.

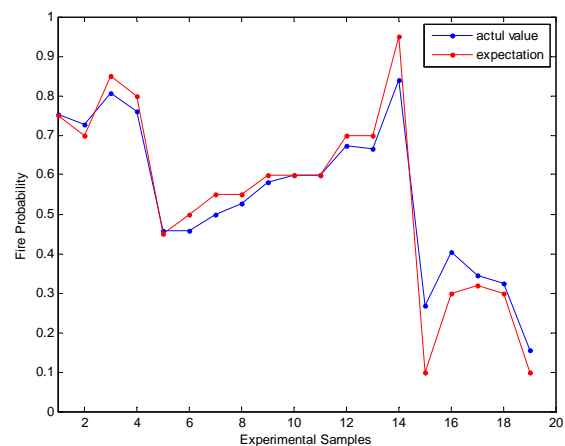


Fig.5 Naked flame probability based on neural network

B. Multi-nodes Fire Confirmation and Fire Source Localization

The simulated experiment was done in office building of 1,000 square meters. The space between two nodes of the wireless sensor networks is 10 meters, and a cluster node should set every 40 square meters shown in Fig.1. We can assess the performance of the system via setting different speed of flame spreading at static wind and different burning intensity. Fig.6 and Fig.7 show the situation at different conditions about 30mins after the fire broke out. In Fig.6, the static wind flame spreads at the speed of 0.2m/min and the burning intensity is 50kJ/m²·s. In Fig.7, the static wind flame spreads at the speed of 0.7m/min, the burning intensity is 220kJ/m²·s.

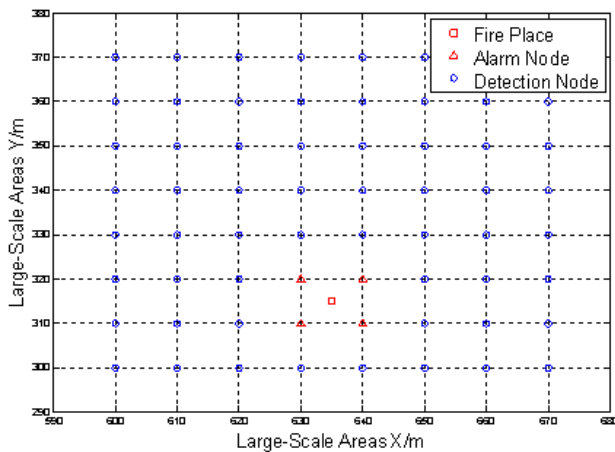


Fig.6 Fire situation at static combustion speed of 0.2m/min

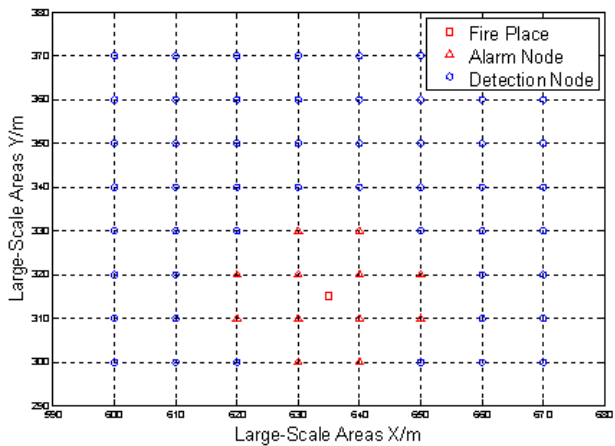


Fig.7 Fire situation at static combustion spread of 0.7m/min

Therefore, the lower the combustion spread speed and the combustion intensity is, the smaller the detected fire range is. And vice versa, the speed of the flame spread is faster and the combustion intensity is stronger, the range of fire detected is also larger.

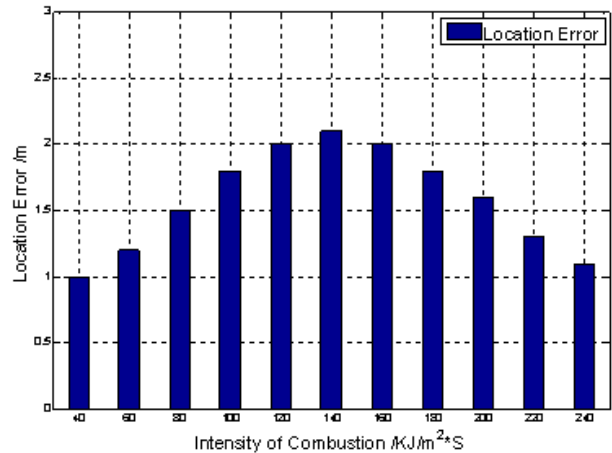


Fig.8 Fire location error vs. fire burning intensity

After the fire hazard and its coverage are confirmed, three valid nodes, whose fire information change fastest, are chose in the confirmed area to locate the fire source collaboratively. Besides, the location error vs. fire burning intensity is shown in Fig.8.

VI CONCLUSIONS

Fire hazard monitoring and evacuation for building environments is a novel application area for the deployment of wireless sensor networks. In large place such as a marketplace, it is crucial for firefighters to know the fire hazard situation, and decide on how to best tackle the disaster. This paper presents an intelligent fire hazard monitoring system for large space based on wireless sensor network, and proposes fire hazard detection algorithm based on neural network for single node, and fire hazard location algorithm using the smoke diffusion model and gas temperature diffusion model for whole wireless networks. Theory analysis and experimental results show that the fire hazard detection and location algorithm could improve the performance of fire hazard detection including accurate location, and can speed up fire warning to reduce property losses.

However, the diffusion model of smoke and temperature and the network architecture are ideal in the paper, and the model and network structure in application should be adjusted in the actual environment to improve the reliability of the system.

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