The application of fusion structure in the coal mine safety state evaluation

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Abstract

Coal mine safety is a very important link in the current coal mine production. Currently, there are a lot of kinds of methods for the evaluation of coal mine safety environment in order to solve the evaluation of the coal mine safety status. However, the complexity and diversity of coal mine environment cause that there is no method can evaluate coal mine safety status. So a new method is proposed, which called two-stage fusion structure according to China's natural environment of the underground coal mine, is used to evaluate the condition of coal mine safety. Firstly, it gets various parameters for affecting the safety of underground using the first level evaluation method; secondly, the second level fusion method is used to realize the coal mine security situation assessment. The experimental results show that this method has better performance more than other methods in evaluating coal mine safety.

Keywords: the first level fusion algorithm, fusion decision, mine safety, better performance

1 Introduction

In recent years, Coal mine disaster accidents frequently happen, which makes people's life lose. It is very important to evaluate the security situation in time, correctly determine the mine safety status to avoid or reduce the coal safety accident [1].

Currently, there are some coal mine safety evaluation methods: expert system, data envelopment analysis method, neural network and support vector machine [2]. Expert evaluation system is mainly based on expert experience and knowledge of coal mine safety, the evaluation results has much to do with expert level, so the evaluation results is difficult to reflect subjectively the degree of coal mine safety; data envelopment analysis is not yet mature, it is difficult to reflect the mapping relation between evaluation index and evaluation results, and at the same time it has certain limitations, the evaluation accuracy is lower. Neural network is a kind of "black box" evaluation method, which needs a lot of sample data for coal mine safety evaluation, but the evaluation results is poor if using the pure quantitative method to evaluate coal mine safety, the same as artificial intelligence [3].

Production of coal mine is a special industry which contains personnel management, machinery operation, mining technology, geological conditions and natural environment, and all the factors have differences [4, 5]. In the coal mine safety evaluation process, firstly, needs to establish a scientific and perfect coal mine safety evaluation, then calculates the index weight, and finally gets the safety level.

Therefore, in order to improve the coal mine safe evaluation accuracy and reliable, the article proposes two-level fusion structure, which is based on improved real-time adaptive weighted fusion algorithm and fuzzy information fusion theory. The method adopts the improved real-time adaptive weighted algorithm to achieve a spatial real-time data fusion which was distributed in different geographical location firstly, and then used Gaussian functions and fuzzy transform information fusion theory to get coal mine safety evaluation. The experimental results show that the method is feasible and effective for multi-sensor mine safety evaluation system.

2 The two-level fusion algorithm structure

Gas, carbon monoxide, oxygen, temperature, wind speed in the air are the fatal factors which affect the safety status under the shaft. This paper puts forward a sensor group which contains gas, carbon monoxide, oxygen, temperature, and wind speed sensors to monitor different positions of a mining area and then using the improved real-time adaptive weighted fusion algorithm to deal with monitoring parameter values to realize the first level data fusion in the spatial domain, and at last adopting the fuzzy information fusion theory to achieve the secondary decision of system. The model of the method is shown in Figure 1.

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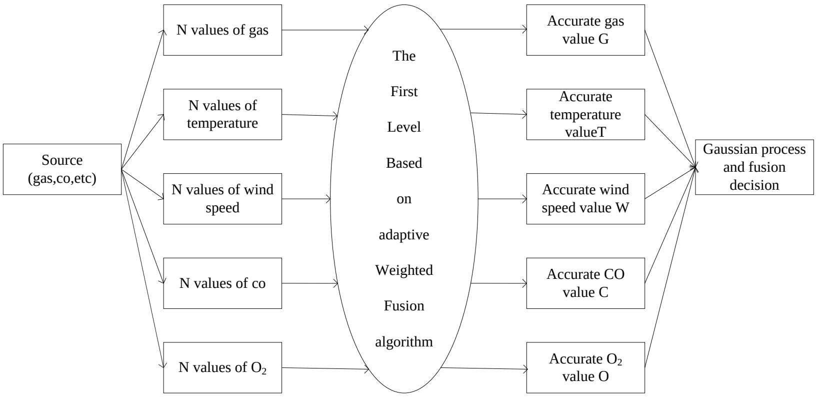

FIGURE 1 The model of two-level fusion structure

3 The first level fuzzy algorithm

The parameters in a mining area are monitored, such as gas, co, and wind speed and so on, and the sensors are distributed in a large scale. To understand the status of the mine safety comprehensively and accurately, multi-sensor groups must be used to complete the task about monitoring data. The parameter, which is monitored by sensor group is more accurate than single sensor. To processing underlying data of system, this paper proposes the real-time adaptive weighted fusion algorithm, which does not need prior knowledge and the programming is easily to realize to get the first level fusion in spatial domain.

3.1 THE FIRST LEVEL FUZZY ALGORITHM

Adaptive weighted fusion algorithm is a common method to fuse the underlying data for multi-sensor. The use of this method is not restricted even in the case of weak or inadequate information [6]. Taking the data from gas sensor as an example, the description of algorithm is as follows:

1) In the coal mine safety evaluation system which contains multi-sensor group, the weight of gas sensor is set as $W_{i1}(\mathrm{i}=1,2,\cdots,n.)$, variance is $\sigma_{i1}^2(\mathrm{i}=1,2,\cdots,n.)$ and W_{i1} is needed to be fulfilled: $\sum_{i=1}^{n} W_{i1}=1$.

2) The gas estimation true value was X, a gas sensor measured value was X_i for a moment, the optimal fusion value $\hat{X}(\mathrm{x})$, which meets the optimal condition that the mean square error was minimum, and the last $\hat{X}(\mathrm{x})$ needs to meet Equation (1):

$$\hat{X}(\mathrm{x})=\sum_{i=1}^{n} W_{i1} X_i \tag{1}$$

The total mean square error of $\hat{X}(\mathrm{x})$ [7]:

$$\sigma^2=E[X-\hat{X}(\mathrm{x})]^2=E[\sum_{i=1}^{n} W_{i1}^2 (X-X_i)^2]+ 2\sum_{i=1,j=1,i\neq j}^{n} W_{i1}W_{j1}(X-X_i)(X-X_j)] . \tag{2}$$

Because X_1, X_2,…, X_n were independent each other $E[(X-X_i)(X-X_j)]=0\ (i\neq j, i, j=1,2,\ldots\mathrm{n})$:

$$\sigma^2=E[\sum_{i=1}^{n} W_{i1}^2 (X-X_i)^2]=\sum_{i=1}^{n} W_{i1}^2\sigma_{i1}^2 . \tag{3}$$

According to the multivariate function extreme value theory, we can calculate the corresponding weighted factor when the total mean square error is minimized [8]:

$$W_{i1}^{*}=1/\sigma_{i1}^2\sum_{i=1}^{n}\frac{1}{\sigma_{j1}^2},\quad i=1,2,\ldots\mathrm{n}. \tag{4}$$

The minimum mean square error is [9]:

$$\sigma_{\min}^2=1/\sum_{i=1}^{n}\frac{1}{\sigma_{i1}^2} . \tag{5}$$

The above estimation is based on the real-time values of the gas sensors in some time, and if the estimation is constant, we can estimate according to average historical data [10]. Estimation and the total mean square error at this time are as follows respectively:

$$\overline{X}=\sum_{i=1}^{n} W_{i1}\overline{X_i}(\mathrm{K}) . \tag{6}$$

$\overline{X}$: The gas optimal fusion for the first level fusion.
K: The frequency for historical data measurement.

$$\overline{\sigma^2}=\frac{1}{K}W_{i1}^2\sigma_{i1}^2=\frac{\sigma_{\min}^2}{K} \tag{7}$$

$\overline{\sigma^2}$: The optimum fusion of the minimum variance.

3.2 THE RESULT OF FIRST LEVEL FUSION

The mine gas concentration which comes from a coal mine safety production monitoring and control system is denoted by X_i (%) and its variance is σ_{i1}^2 and weights W_{i1}. The properties of each sensor, as X_i, is displayed in Table 1.

TABLE 1 The properties of the gas sensor σ_{i1}^2

G_i	G_1	G_2	G_3	G_4	G_5	G_6
X_i	0.54	0.55	0.45	0.22	0.57	0.44
σ_{i1}^2	0.53	0.48	0.54	0.53	0.39	0.44
W_{i1}	0.151	0.166	0.147	0.152	0.203	0.181

By Equation (6), we could calculate the optimal fusion value of gas concentration 0.4678.

The system could obtain the optimal fusion about temperature, wind speed, etc. by using the above method.

The improved adaptive weighted fusion method is implemented in the first level of data fusion to get relatively accurate parameter information. As the parameters are independent and it is difficult to assess the condition about mine. So the system is required to use fuzzy information fusion theory to realize the secondary fusion processing.

4 The second level fuzzy algorithm

A precise method to describe the association between parameters is very difficult because underlying parameters from the first level fusion are independent. So the application of fuzzy information fusion theory is helpful to make the coal mine security situation evaluation more accurate.

4.1 THE THEORY OF SECOND LEVEL FUSION

Making the absolute subordinate relations of general set become flexibly and the elements to membership of collection can take any value in [0,1] are the basic idea of fuzzy set. The idea is suitable for describing and processing uncertainty sensor data [10, 11]. The theory, which is based on Gaussian membership function and fuzzy transformation can make decisions in the secondary fusion processing of evaluation system.

(U,V,R) is the fuzzy comprehensive evaluation model [13], U is comment set, and V is factors set. n kinds of coal mine safety status and the status collection: $\{U_1,U_2\cdots U_n\}$; the first level fusion feature parameters constitute a collection $\{V_1,V_2,\cdots V_m\}$. R_{ij} is the possibility of status set from characteristic parameter. It is the degree of membership to U_i and V_j, at last it constitutes a fuzzy relation matrix R. The factors weight vector: $A=(A_1,A_2,\cdots A_m)$ is derived from the different influence degree of characteristic parameters for judging result.

The fuzzy transformation is as follows: $B=A\circ R=(B_1,B_2,\ldots,B_n)$,

$$B=(A_1,A_2,\ldots,A_m)\circ\begin{pmatrix}R_{11} & R_{12} & \cdots & R_{1n}\\ R_{21} & R_{22} & \cdots & R_{2n}\\ \vdots & \vdots & \cdots & \vdots\\ R_{m1} & R_{m2} & \cdots & R_{mn}\end{pmatrix}, \quad (8)$$

B : The possibility of coal mine safety status,
A : The factor weight vector,
R : The fuzzy matrix,
B_j : The degree of membership of fuzzy subsets about the comprehensive evaluation of down-hole safety status.

4.2 THE RESULT OF SECOND LEVEL FUSION

The gas concentration, temperature, wind speed, co concentration and oxygen concentration are the main factors, which affect the coal mine safety; the first level fusion structure achieves data fusion from different sample point to the same parameters in spatial domain. For secondary decision-making fusion, firstly, the first level fusion parameters are given different weights according to the experimental data and then get weight vector $A^*(A_1^*,A_2^*,A_3^*,A_4^*,A_5^*)$, it is the first step to realize fuzzy information fusion algorithm. Next, it is time to make sure the degree of membership of each coal mine status from the environment parameters.

For continuous analogy parameter variable, Cauchy fuzzy sets and Gaussian pattern matching algorithm are two different mathematical methods to seek membership [12]. Because constructing the process of Cauchy fuzzy sets is more complex and Gaussian membership function is chosen, the basic idea is as follows: { N_1, N_2,…, N_n } makes up of n kinds of status in status database, where N_i ($i=1,2\cdots,n$) represents different status and each status corresponding to a standard joint feature vector containing k characteristic parameters: $\overline{N}_i=\{N_{i1},N_{i2},\cdots,N_{iK}\}$, $N_{ij}(j=1,2,\cdots,K)$ represents the j^{th} standard characteristic parameter of the i^{th} kind state. All kinds of parameter respectively can become a vector containing K characteristic parameters after the first level fusion in a period of time; $\overline{X}_i=(X_{i1},X_{i2},\cdots,X_{iK})$, where $X_{ij}(j=1,2,\cdots,K)$ represents the j^{th} characteristic parameter of the i^{th} kind state.

For the i^{th} kind condition:

Cauchy fuzzy sets and Gaussian pattern matching algorithm are two different mathematical methods to seek membership [12]. Because constructing the process of Cauchy fuzzy sets is more complex and Gaussian membership function is chosen, the basic idea is as follows: { N_1, N_2,…, N_n } makes up of n kinds of status in status database, where N_i ($i=1,2\cdots,n$) represents different status and each status corresponding to a standard joint feature vector containing k parameters: $\overline{N}_i=\{N_{i1},N_{i2},\cdots,N_{iK}\}$, $N_{ij}(j=1,2,\cdots,K)$ represents the j^{th} standard characteristic parameter of the i^{th} kind state. All kinds of parameter respectively can become a vector containing K characteristic parameters after the first level fusion in a period of time; $\overline{X}_i=(X_{i1},X_{i2},\cdots,X_{iK})$, where $X_{ij}(j=1,2,\cdots,K)$ represents the j^{th} characteristic parameter of the i^{th} kind state.

For the i^{th} kind condition:

1) Membership functions of the parameters:

$$\mu_{N_{ij}}(X_{ij}) = \exp\left(-\frac{(X_{ij}-N_{ij})^2}{2\sigma_{ij}^2}\right). \tag{9}$$

X_{ij} : The j^{th} characteristic parameter of the i^{th} kind state.

N_{ij} : It means the j^{th} standard characteristic parameter of the i^{th} kind state.

σ_{ij}^2 : It means the j^{th} standard deviation of the i^{th} kind state.

2) Vector membership function:

$$\mu_{\overline{N_j}}(\overline{X_i}) = \sum_{t=1}^{K} \alpha_t \times \mu_{N_{ij}}(X_{ij}). \tag{10}$$

$$\sum_{t=1}^{K} \alpha_t = 1, \alpha_t > 0, t = 1, 2, \cdots, K. \tag{11}$$

α_t : It represents the weight coefficient of the t^{th} characteristic parameter.

3) The result of fuzzy transform:

$$B = A^* \circ \mu_{\overline{N_j}}(\overline{X_i}) =$$

$$(A_1^*, A_2^*, A_3^*, A_4^*, A_5^*) \circ \begin{pmatrix} \mu_{\overline{N_1}}(\overline{X_1}) & \mu_{\overline{N_1}}(\overline{X_2}) & \mu_{\overline{N_i}}(\overline{X_3}) \\ \mu_{\overline{N_2}}(\overline{X_1}) & \mu_{\overline{N_2}}(\overline{X_2}) & \mu_{\overline{N_2}}(\overline{X_3}) \\ \mu_{\overline{N_3}}(\overline{X_1}) & \mu_{\overline{N_3}}(\overline{X_1}) & \mu_{\overline{N_3}}(\overline{X_3}) \\ \mu_{\overline{N_4}}(\overline{X_1}) & \mu_{\overline{N_4}}(\overline{X_2}) & \mu_{\overline{N_4}}(\overline{X_3}) \\ \mu_{\overline{N_5}}(\overline{X_1}) & \mu_{\overline{N_5}}(\overline{X_1}) & \mu_{\overline{N_5}}(\overline{X_3}) \end{pmatrix}. \tag{12}$$

5 Results and analysis

The elements in B represent respectively three kinds of status: safety, generally safety and dangerous. The influence degree of each sensor group in system was different, this paper set the gas (G), temperature (T), wind speed (V) and carbon monoxide (C) and oxygen (O) as the weight vector $A = (0.21, 0.13, 0.37, 0.17, 0.12)$ through parameters test and data analysis for many times in one coal mining.

TABLE 2 Fuzzy matrix

Evaluation factors	Safety state	General safety	Dangerous state
G	0.520	0.480	0
T	0.240	0.740	0.020
V	0.123	0.637	0.240
C	0.162	0.420	0.418
O	0.105	0.213	0.682

For a certain moment, the system transmitted the five parameters from the first level fusion to the centre of decision fusion, then the fusion centre could get the fuzzy matrix according to Gaussian membership function and at last the system compounded and normalized processing the weight vector of characteristic parameters and fuzzy matrix to realize safety status evaluation coal mine.

We could get the fuzzy matrix from Equation (9), (10) and (11), fuzzy matrix in Table 2:

We could get the result from Equation (12): $(B_1, B_2, B_3) =$

$$(0.21, 0.13, 0.37, 0.17, 0.12) \circ \begin{pmatrix} 0.520 & 0.480 & 0 \\ 0.240 & 0.740 & 0.020 \\ 0.123 & 0.637 & 0.240 \\ 0.162 & 0.420 & 0.418 \\ 0.105 & 0.213 & 0.682 \end{pmatrix}.$$

$=(0.274, 0.440, 0.256)$

The fusion degree of membership of B_2 is the largest; we could determine "general safety" as coal mine status at the moment according to maximum membership judgment rules.

Every sensor group degree of membership value is presented in Table 3. We got down-hole safety determination according to decision rules and at same time obtained comprehensive judgments on the basis of fuzzy subset.

TABLE 3 The contrast between single sensor recognition and fusion recognition

Mine state	Factors	Safety	General safety	Dangerous	Results
Safety	G	1.000	0	0	Safety
	T	0.820	0.180	0	Safety
	V	0.505	0.327	0.168	Safety
	C	0.328	0.473	0.199	General safety
	O	0.256	0.323	0.421	Dangerous
	Fusion	0.422	0.373	0.168	Safety
General safety	G	0.520	0.480	0	Not sure
	T	0.240	0.740	0.020	General safety
	W	0.123	0.637	0.240	General safety
	C	0.162	0.420	0.418	Not sure
	O	0.105	0.213	0.682	Dangerous
	Fusion	0.274	0.440	0.256	General safety
Dangerous	G	0	0.050	0.950	Dangerous
	T	0	0.180	0.820	Dangerous
	W	0.327	0.311	0.362	Dangerous
	C	0.103	0.324	0.573	Dangerous
	O	0.231	0.572	0.197	General safety
	Fusion	0.265	0.345	0.390	Dangerous

Through experimental contrast, it can be seen that one kind sensor for the evaluation of mine safety status is uncertain, but the application of fuzzy fusion increases credibility of state evaluation, enhances and improves the performance of the safety evaluation system.

6 Conclusions

The two-level fusion structure is proposed in this paper, which based on data fusion technology in spatial domain and information fusion algorithm. With the two-stage fusion structure implemented in coal mine safety evaluation system, the contrast experiment shows that the improved adaptive weighted fusion algorithm disposes the data on the space is more reliable, and at same time, fuzzy fusion algorithm in the secondary structure can improve the credibility of the whole evaluation system. Therefore, the practical application of structure in coal mine safety evaluation is feasible. Besides, the time complexity algorithm needs to be part of our future.

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