Fuzzy clustering algorithm of early fire based on process characteristic

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Abstract
Traditional fire detection technologies usually measure the smoke particles or the temperature increase resulted from fire. However, in the early stage of fire, few particles and low heat are generated. Current fire algorithms is based on comparing the fire variables with a given threshold value, the transient sampled values are often affected by some stochastic disturbances. Consequently current methods are hardly alarm fire fleetly and reliably and often give false or failing alarm.

A new fire detecting technology was presented based on early fire process signature and fuzzy clustering algorithm. The process eigenvector is made up of CO concentration in detected environment as well as its increasing rate and acceleration. The eigenvectors are divided into two categories of real fire and non-fire, the two cluster centers are obtained by using fuzzy clustering analysis. According to threshold membership principle, the real fire sources can be distinguished from non-fire sources successfully. The result of experiments has shown that the presented technology is feasible for early fire detecting with lower rate of false and failing alarm, and give fire alarm much early than any other traditional method.

Keywords: Early fire detection, process characteristic, fire signature, fuzzy clustering

1. Introduction
Traditional fire detection technologies usually measure the number density of particles in smoke using ionic or photoelectric smog-sensing detectors, or monitor the temperature increase resulted from fire using thermal detectors [1]. However, in the early stage of a fire, specially in slow fire or smoldering fire, only a small amount of particles are generated and low heat is outputted. Consequently smog-sensitive and thermo-sensitive detectors can be only used in fast fire or flame fire which produced large quantities of smoke and heat, it is impossible for them to alarm fire rapidly in the early stage of a fire. In fact that large amount of CO, one of the primary fire signatures, would generate in smoldering fire, early fire detection can actualize by monitoring the increase of concentration of CO [2, 3]. On the other hand, traditional fire detection arithmetic makes fire decision depended on comparing the absolute value of fire variables sampled instantaneously with a given threshold, it often give false alarm or failed alarm consequently. In this paper, a new fire diagnosis technology was presented based on the process eigenvector of early fire signature and fuzzy cluster algorithm.

2. Experiment
According to the national standard fire, a series of fire test to some candidate materials have performed in the fire detection system based on NEXUS Fourier transformation infrared
spectrometer with a 10 meters gas pool, the spectrum detector of the experiments is MCT-A with the resolution of 4 cm\(^{-1}\), the infrared absorption wavebands of CO are selected from 2165 cm\(^{-1}\) to 2183 cm\(^{-1}\) and from 2188 cm\(^{-1}\) to 2203 cm\(^{-1}\), the sample frequency is 64 times per minute. By FTIR quantitative analysis, the concentration of CO can be obtained during the burning process started from heating to combustion finished [2].

The experiment materials include 6 kinds of real fire source, such as pieces of plywood, wood block, towel, cotton rope, paper and litter bag which was filled with some scraps of paper and ignited by a smoldering cigarette, and 3 kinds of non-fire nuisance source such as burning candle, cigarette smoke and burning liquefied petrochemical gas (LPG). The test results have shown that CO concentration of real fire increases about 10 minutes later from heating, but that of non-fire have no obvious uptrend of growth and keeps in small values during the whole combustion process [4]. This character offers a possibility to distinguish real fire from non-fire nuisances in the early stage of fire.

3. **Extraction of early fire process characteristic**

   The essential difference between real fire and non-fire consists in the CO concentration and its increasing rate and acceleration. Supposing that \(x(n)\) is CO concentration, \(x'(n)\) and \(x''(n)\) are respectively the rate and acceleration of \(x(n)\) in the time \(n\), then the fire process characteristic can be expressed by the eigenvector \([x(n), x'(n), x''(n)]\), \(n=1,2,3, \ldots\)

   At the time \((n+m)\), CO concentration can be expressed by the eigenvector in the time \(n\)

   \[
   x(n+m) = x(n) + mx'(n) + \frac{1}{2} m^2 x''(n) + e(m)
   \]

   Where \(e(m)\) is estimation error. To make eigenvector optimal, the objective function \(J_i\) must be minimum nearby time \(n\), where \(m=-k-k\), weight function \(w^2(m)=0.54+0.46\cos(\pi m/k)\).

   \[
   J_i = \sum_{m=-k}^{k} w^2(m)e^2(m) = \text{min}
   \]

   The three elements of eigenvector can be extracted from sampled data by formula (3).

   \[
   \begin{pmatrix}
   x(n) \\
   x'(n) \\
   x''(n)
   \end{pmatrix} = \sum_{m=-k}^{k} w^2(m) \begin{pmatrix}
   1 & 0 & m^2/2 \\
   0 & m^2 & 0 \\
   m^2 & 0 & m^4/2
   \end{pmatrix} \sum_{m=-k}^{k} w^2(m) \begin{pmatrix}
   x(n+m) \\
   mx(n+m) \\
   m^2x(n+m)
   \end{pmatrix}
   \]

   The half-breadth \(k\) of the weight function is an important parameter to be selected; the characteristic curve will become smoother while \(k\) increases. A very smooth characteristic curve can reflect the microcosmic characters of fire process, but it will delay the time of fire alarm. If \(k\) is too small, the sensitivity of fire alarm can be improved well, but the eigenvector is affected by more stochastic errors, which will result in false alarm or failed alarm. Therefore the value of \(k\) should be selected based on experiments.

   Eigenvector describes CO dynamic change of information from time \((n-k)\) to \((n+k)\), which reflects the fire signature in the process including fire occurrence and development. So using the eigenvector to distinguish real fire from nuisance fire is based on fire process signature in a given period of time instead of transient sampled value of fire variables like any traditional method. The extraction results of process eigenvectors of 9 candidate materials are shown in Fig. 1, where \(k=3\). It is evident that CO concentration as well as its rate and
acceleration increase fleetly in the case of real fire sources, but the eigenvectors of non-fire nuisance sources change infinitesimally in all the process of combustion.

4. Fuzzy clustering algorithm based on process characteristic

As shown in Fig. 1 (d), the vector from the origin in coordinate system to the eigenvector of non-fire centralizes almost in the origin, but that of real fire deviates far from the origin with in short time. All the eigenvectors can be divided into two sorts by using fuzzy clustering.

Suppose $X=[x_1,x_2,…,x_n]_{3×n}$, $V=[v_1,v_2]_{3×2}$, $U=[u_{ij}]_{2×n}$, where $X$ is the set of eigenvector estimated from sampled data in fire test. $V$ is a matrix of clustering center of eigenvectors; $v_1$ and $v_2$ are $3×1$ order vectors which express the two clustering centers of non-fire and real fire. $U$ is matrix of membership grade, and $u_{ij}$ is the membership grade of eigenvector $j$ belong to clustering center $i$, and $1≤i≤n, 1≤j≤2$, $0≤u_{ij}≤1$ and $u_{i1}+u_{i2}=1$. The key problem of distinguish real fire source from non-fire can be express as that search out two optimization clustering centers $V$ and make the objective function $J_2$ minimum.

$$J_2(U,V) = \sum_j \sum_i u_{ij}^2 d_{ij}^2$$

(4)

After $k$ times iteration by using iteration method, the new $U$ and $V$ are expressed below

$$u_{ij}(k) = \left( \sum_{r=1}^{2} \frac{d_{ij}^r(k)}{d_{ij}^r(k)} \right)^{-1}$$

(5)

$$v_i(k+1) = \frac{\sum_{j=1}^{n} u_{ij}^r(k) x_j}{\sum_{j=1}^{n} u_{ij}^r(k)} \left( \sum_{j=1}^{n} u_{ij}^r(k) \right)^{-1}$$

(6)

Where $d_{ij}(k)=\|x_j-v_i\|$ is Euclidean distance from $x_j$ to $v_i$. Within limits of permissible error $\varepsilon$, terminate iterating operation if $\|V(k)-V(k+1)\|<\varepsilon$. by this time $V(k)$ is the final optimization clustering centers, and $U(k)$ is the final matrix of membership grade.

As a training process of the iteration method, 282 data from fire test, including 164
samples from non-fire source and 118 samples from real fire source, were selected and the iterated operation was run according to formula (4) ~ (6). The result of training is shown in Fig. 2, where \( \varepsilon = 0.001 \). Figure 2 shows that the presented algorithm has better stability and higher convergence rate. The blue star and the red hexagram in Fig. 2 (b) and Fig. 1 (d) indicate the clustering centers of non-fire \( v_i \) and that of real fire \( v_2 \). The final optimization clustering center \( V \) is confirmed below.

\[
V = [v_1, v_2] = \begin{bmatrix} 2.5154 & 44.6055 \\ 0.5027 & 3.3052 \\ 0.0931 & -0.0455 \end{bmatrix}
\]

(7)

To make a right decision of fire or non-fire, the membership grade \( u_{ij} \) of an eigenvector \( x_j \), which is extracted from some sampled data in certain period of time in burning test, must be calculated by formula (5) and (7). According maximum membership principle, the eigenvector \( x_j \) ought to belong to the cluster \( i \) to which its membership grade \( u_i \) is the biggest, i.e. \( u_i = \text{max}(u_{ij}, u_{2j}) \). Whenever fire alarm is sent out in case of \( i = 2 \), otherwise if \( i = 1 \) no fire takes place. As a simple fire detection algorithm, maximum membership principle can be used to distinguish the real fire source from non-fire nuisance sources.

In online fire detection, the occurrence and development of fire is often a very slow and long process, even if a fire occurs, the membership grade of the eigenvector \( x_j \) belong to \( v_2 \) increases gradually from 0 to 1. In the case of that \( u_{ij} \) is closed to \( u_{2j} \) and is about 0.5, the decision of \( x_j \) belongs to either cluster 1 or cluster 2 is all improper. Therefore maximum membership principle is not applicable for continuous online fire detection, unless the membership grade is much bigger than a given threshold value \( \delta \), in general \( \delta = 0.58 \). If the biggest membership grade is approximate to 0.5, the algorithm ought to reject making a fire decision and wait for next loop of data sampling to refresh the eigenvector. This algorithm is called threshold membership principle. As a two clustering problem, the fuzzy clustering fire decision of fire algorithm is expressed as follow.

\[
D(f) = \begin{cases} 
0 & \text{non-fire } \text{ if } u_{2j} \geq \delta \\
1 & \text{fire alarm } \text{ if } u_{2j} < \delta 
\end{cases}
\]

(8)

In order to inspect the validity of presented fire detection method, nine candidate materials were burn in fire laboratory. In each burning test, the raw data of CO concentration are sampled continuously from heating start with the frequency of 64 times per minute, the eigenvectors are extracted one after another by using formula (3), as shown in Fig. 1 (d). The membership grade of eigenvectors belong to two clustering centers can be calculated from formula (5) and (7). Figure 3 (a) shows the membership grade \( u_{2j} \), and Fig. 3 (b) shows the fuzzy clustering decision of fire based on formula (8). Figure 3 reveals that the membership grade of non-fire nuisance sources belong to ‘fire’ is almost 0 during the entire combustion process, but the membership grade of real fire sources belong to ‘fire’ has approached to 1 in
the very early stage of fire. So using fuzzy clustering algorithm based on process characteristic can distinguish real fire from non-fire sources reliably without both false alarm and failing alarm.

The fire warning time of the presented algorithm can be read from Fig. 3 (b), as shown in Table 1.

In order to investigate the timeliness of the presented method and make a comparison to current detection methods, the earliest warning time of fire detectors, such as ionic smoke detector, photoelectric smoke detector and temperature detector, fixed in laboratory had been recorded. The comparison is shown in Table 1. Obviously presented algorithm fire alarm is much early than any others.

5. Conclusion
A fuzzy clustering algorithm of early fire based on process characteristic is put forward in this paper. The fire process eigenvector is made up of CO concentration and its increasing rate and acceleration in the early stage of a fire, all the eigenvectors can be divided into two categories of real fire and non-fire. According to threshold membership principle, the fuzzy clustering algorithm can distinguish real fire and non-fire sources sensitively and reliability. The result of experiments has shown that the presented algorithm is feasible for early fire detection with lower rate of both false alarm and failing alarm, and give fire alarm much early than any other traditional method.

References