Data fusion algorithm for rapid multi-mode dust concentration measurement system based on MEMS

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Abstract. As single measurement method cannot fully meet the technical requirements of dust concentration measurement, the multi-mode detection method is put forward, as well as the new requirements for data processing. This paper presents a new dust concentration measurement system which contains MEMS ultrasonic sensor and MEMS capacitance sensor, and presents a new data fusion algorithm for this multi-mode dust concentration measurement system. After analyzing the relation between the data of the composite measurement method, the data fusion algorithm based on Kalman filtering is established, which effectively improve the measurement accuracy, and ultimately forms a rapid data fusion model of dust concentration measurement. Test results show that the data fusion algorithm is able to realize the rapid and exact concentration detection.

1. Introduction
Industrial dust explosion accidents occur frequently and respiratory diseases caused by dust particles emitted from industrial production have been more and more common in recent years, thus it is of great practical significance for the control of environmental pollution and human health to limit the concentration of dust [1]. How to accurately measure the dust concentration is a key step in dust control. Previous studies have shown that the detection effect is difficult to meet the practical needs of dust detection projects when using a single measurements method for dust concentration measurement [2]. To solve this problem, we have developed a multi-mode dust concentration measurement system based on multiple MEMS sensors suitable for use in detection of industrial dust.

To get the accurate results when simultaneously measuring the same target with several different measurement methods, it needs to perform deep level fusion in sensing units, measure circuits or solution algorithms, thus the measurement performance or the data of detection can be complementary to each other to compensate for the defects of the single measure method and complete the rapid, accurate and efficient detection of the complex measure object [3].

Multi-mode detection method is a kind of organic combination of different detection methods. Different methods need to be fused at different levels in sensing unit, measure circuit or solution algorithm, and data fusion is the core of multi-mode detection [4]. Data fusion algorithm can improve the detection accuracy and resolution, but at the same time it will bring a certain amount of calculation, which results in increasing computing time and computing resources. How to choose the optimal multi-source data fusion algorithm based on the calculation model characteristics and detection characteristics of the basic detection method, and form the optimal match between the detection speed and the detection precision is the core problem of the fusion algorithm [5].
2. Measuring system

Typically, according to the difference of system architecture, multi-sensor data fusion detection system can be divided into the centralized, the distributed and the mixed types. The structure of the proposed multi-mode detection system in this paper is relatively simple, but the relationship of data is more complex, because both of the ultrasound field measure method and the electric field measure method are required to be compensated by environmental parameters, so the mixed system structure has been chosen, that not only can guarantee the system to achieve good integration, but also to make full use of the advantage of the simple structure system, to avoid a huge calculation and lots of communication tasks. The final design of the system is shown as follows:

![Diagram of Multi-mode Measuring System](image)

Figure 1. Multi-mode measuring system schematic diagram

The method of ultrasound field detection is mainly based on the theory of ultrasound attenuation: absorption attenuation and scattering attenuation are produced in the propagation of ultrasound in the medium, and attenuation level is represented by attenuation coefficient $\alpha$. Absorption, attenuation and scattering attenuation are the processes of energy conversion and dissipation in a propagating medium. The attenuation coefficients $\alpha$ contains characteristic information of the propagating medium. Therefore, the concentration of the mixture can be detected by measuring the acoustic attenuation coefficient [6].

The electric field detection method is mainly based on the equivalent dielectric constant theory: different substances have different dielectric constants, and the mixture also has an equivalent dielectric constant, which is determined by the composition of the mixture and its mixing ratio, that is, when the composition is known, the equivalent dielectric constant contains the proportionality information of the different components. Therefore, the density of the mixture can be calculated by measuring the dielectric constant of the mixture using a capacitive sensor with fixed structural parameters [7].

According to the measuring system principle, the concentration measurement system which is designed in this paper includes at least the MEMS capacitance sensor, MEMS ultrasonic sensor, the signal driver module, the signal receiving and amplifying module and the control & calculation module, in addition it should have the power supply and the certain peripheral circuits.

3. Algorithm

Kalman filter algorithm is a data processing method based on recursive and error estimation. The method optimizes the statistical characteristics of the current data according to the error estimation and the data detection value of the previous state, thus providing the filter (corrected) calculated value of the current detection value [8]. The data fusion method based on Kalman filter algorithm is to calculate the weighted average of multiple sensor data. The weight of each sensor data is inversely proportional to its detection variance. Because of the recursive computing idea, the method has good computational characteristics, which is easy to implement in the programming language, and has high computational real-time and sufficient computational precision. Therefore, Kalman filter has been widely studied and applied [9]. The mathematical principle of the Kalman filter algorithm is given as follows:
Assume that the state equation and the detection equation of the dynamic measuring system are respectively:

\[ X_k = \Phi_{k,k-1} X_{k-1} + \Gamma_{k,k-1} W_k \]  
\[ Z_k = H_k X_k + V_k \]

In the above equation (1) and (2), \( X_k \) is the system state at time \( k \), \( \Phi_{k,k-1} \) and \( \Gamma_{k,k-1} \) are the state transition matrix at time \( k-1 \) to time \( k \), \( Z_k \) is the detection value at time \( k \), \( H_k \) is the parameter of the detection system, \( W_k \) and \( V_k \) represent the Gaussian white noise of the system process and the observation.

If the estimated state and observations satisfy equation (1), the system process noise and the observation noise satisfy equation (2), then the estimated value \( \hat{X}_k \) of the observed \( X_k \) at time \( k \) can be solved according to the following equation.

Further predicted:

\[ \hat{X}_{k,k-1} = \Phi_{k,k-1} \hat{X}_{k-1} \]  
State estimated:

\[ \hat{X}_k = \hat{X}_{k,k-1} + K_k [ Z_k - H_k \hat{X}_{k,k-1} ] \]

Filter gain matrix:

\[ K_k = P_{k,k-1} H_k^T R_k^{-1} \]

Predicted estimate covariance:

\[ P_{k,k-1} = \Phi_{k,k-1} P_{k-1,k-1} \Phi_{k,k-1}^T + Q_k \]

Updated estimate covariance:

\[ P_k = [ I - K_k H_k ] P_{k,k-1} \]

The above is the five basic formulas of the Kalman filter [10]. From the above reasoning, once given the initial values \( X_0 \) and \( P_0 \), according to the observed value \( Z_k \) at time \( k \), we can recursively calculate the state estimation \( \hat{X}_k \) at time \( k (k=1,2,\ldots,N) \).

According to the Kalman filter model, when there is a dust concentration detection using the ultrasound field method and the electric field method respectively, there is a system state equation (8) and two detection equation (9) and (10):

\[ X_k = \Phi_{k,k-1} X_{k-1} + \Gamma_{k,k-1} W_{k-1} \]  
\[ Y_k^1 = H_k^1 X_k + V_k^1 \]  
\[ Y_k^2 = H_k^2 X_k + V_k^2 \]

If the detection noise variance matrices \( R_i^j \) and \( R_i^2 \) guarantee that \( H_k^{1T} R_1^1 H_k^1 + H_k^{2T} R_2^2 H_k^2 \) is a nonsingular matrix, the state value \( X \) has a linear minimum variance estimation:
\[ \hat{X} = R (H_k^1 R_{1}^{-1} Y^1 + H_k^2 R_{2}^{-1} Y^2) \]  

(11)

The generalized detection vector can be defined as:

\[ Y_K = [Y_k^1 \ Y_k^2] \]  

(12)

Then the generalized detection equation as follows:

\[ Y_K = H_K \hat{X}_K + V_K \]  

(13)

\[ H_K = [H_k^1 \ H_k^2]^T \]  

(14)

\[ V_K = [V_k^1 \ V_k^2]^T \]  

(15)

According to the classical Kalman filter algorithm and the optimal fusion estimation theorem [11], the iterative algorithm of multi-sensor data fusion algorithm can be obtained as follows:

\[ \hat{X}_k = \hat{X}_{k,k-1} + K_k [Y_k^1 - H_k^1 \hat{X}_{k,k-1}] + K_k^2 [Y_k^2 - H_k^2 \hat{X}_{k,k-1}] \]  

(16)

\[ P_k = [P_{k,k-1}^{-1} + (H_k^1 R_{k}^1 H_k^1)^{-1} + (H_k^2 R_{k}^2 H_k^2)^{-1}]^{-1} \]  

(17)

4. Sample Test

In order to evaluate the effect of the above algorithm, the effect evaluation and verification of the data fusion algorithm are further studied. The research process is as follows:

Step 1. The initial data acquisition

To generate the standard environment of even dust concentration, we use customized dust chamber, and the dust concentration was measured by the ultrasound field method and the electric field method with MEMS sensors respectively. The data of the dust stabilization stage were selected as the analysis object, and the data length was 150 points. The concentration curves obtained from the two test methods are as follows:

![Figure 2. Dust concentration value measured by ultrasound field method](image)

It can be seen from the graph that the system noise of the dust concentration value obtained by the electric field method is larger than that of the sound field method, but the trend of the concentration detection value of them is basically the same, which indicates that the dust concentration cannot be
accurately detected by a single measure method.

![Figure 3. Dust concentration value measured by electric field method](image)

**Step 2. Extraction of state equations and measure equations**

Using the MATLAB software to analyze the two sets of data, we can get the corresponding linear fitting curve and the corresponding noise variance, as follows:

\[
\hat{X}_k = \hat{X}_{k,k-1} + K_k [Y_k - H_k^T \hat{X}_{k,k-1}] + K_k^2 [Y_k^2 - H_k^2 \hat{X}_{k,k-1}] 
\] (18)

\[
P_k = [P_{k,k-1}^{-1} + (H_k^T R_k H_k^{-1})^{-1} + (H_k^2 R_k^2 H_k^2)^{-1}]^{-1} 
\] (19)

The above two formulas are used as the true dust concentration state equation, the detection equation of ultrasound field method and the electric field method, and the corresponding data variance is used as the noise variance of the detection equation.

**Step 3. Data fusion processing**

According to the data fusion model, we use MATLAB software to program for acoustic-electrical data fusion, and compare with the concentration value obtained by the single detection method, the contrast curves was shown as follows:

![Figure 4. Comparison curves between measured values and processed values](image)

As can be seen from the figure, with the use of data fusion algorithm, the detection noise of the dust concentration data is significantly reduced, effectively improve the accuracy of concentration data.
5. Conclusion
According to the comparison of the curves shown above, it can be seen that the acoustic-electrical data fusion model based on Kalman filter effectively reduce the detection error and the detection noise, so as to effectively improve the measuring system’s measure precision and obtain more reliable dust concentration data. Therefore, the multi-sensor data fusion model and algorithm based on Kalman filter we present in this paper are reasonable and effective.

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