Analysis of Quartz Resonator Array Based on Data Fusion Technology for High Performance Thermal Sensors

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Abstract

In order to improve the accuracy and reliability of temperature measurements, put forward a kind of high precision non-contact temperature measuring system, which is composed of the quartz temperature sensor array and microprocessors. The sensor used by the system is the quartz tuning fork non-contact temperature sensor based on polymer line, and the polymer line that is highly sensitive to temperature is as the sensitive element, in combination with quartz tuning fork resonator that is not sensitive to the temperature , and they form the high precision temperature sensor together. Compared with the traditional thermometry, set up a new temperature sensor array to measure temperature, which uses the Bayes estimation to fuse the data measured by the temperature sensor array, and calculate the accurate temperature measurements. The experimental results shown that the measurement precision of sensing system is 0.02℃, and the sensitivity is 71.5×10^{-6}/℃within temperature range from 0°C to 100°C.The system has advantages of the high precision, and the good stability, and reliable performance, etc.

Keywords: Quartz temperature sensor based on polymer line; Sensor array; Data fusion; Bayes estimation

1. Introduction

Temperature is the most basic environmental parameter, almost all the reactive processes of the chemical and the physical changes are closely related to the temperature. Temperature has a absolute contact with people's daily life and the agricultural production and the machinery manufacturing, the steel, the pharmaceutical, the food processing, the metallurgy and so on [1]. At the same time, the temperature is also one of the most important process parameters in industrial productions. Nowadays, the industrial productive process achieves automation gradually, and one of the most critical factors is to control and measure the temperature. Therefore, measuring temperature reliably and accurately can guarantee the reproducibility of product quality and the stability of the process better, and it is the most important and critical link to improve the efficiency of the product. With the development of advanced technology, the reliability and the accuracy of the temperature measurement has become more and more important [1-3].

Contacting to measuring the temperature cannot meet the requirements of the industrial temperature measurement completely, because it can only detect the thermal equilibrium temperature that the measured objects reached the balance with the temperature sensors eventually, and it needs a long time to react. It is not suitable for applying in the situation of the fast change and the smaller measured objects, which makes the use of the non-

contact temperature measurement is limited. Non-contact temperature measuring commonly uses the principle of infrared measuring temperature to realize. The wireless infrared radiation temperature measurement was rapid and accurate, and the measuring process can not change temperature of the measured object, and influences of the air and the environment *etc.*, factors on temperature measurement are also small. It not only overcomes the problem existing in the contact temperature measurement, but also has advantages of the high sensitivity and the wide temperature range, and showing the surface temperature field and storage and process. But the realization of the infrared temperature measurement with the high precision is still limited a lot.

With the in-depth demand for non-contact temperature measuring, professors in the domestic and abroad have developed a variety of temperature sensors, which are suitable for non-contact temperature measurement. For the application of non-contact temperature measurement, Dastkos *et al.*, use it to the imaging, and Gimzewski *etc.*, use it to the chemical and the biological sensors. Although the sensitivity of some temperature sensors is very high ideally, and almost can reach 0.1mK, it is difficult to be applied in the actual measurement. In 1996, the P.G.Datskos team published the non-contact temperature sensor based on piezoresistive micro cantilever beam in applied physics letters, while the theoretical sensitivity is as high as 0.01mK,no experimental proof it. In a word, the sensitivity of this kind of sensor is not high and the accuracy is limited. Therefore, to develop a low cost and high precision non-contact temperature sensor will be the main development trend [4-6].

The paper uses the new sensor array to measure temperatures, and the sensor array can make a rapid accurate judgment to the change of the environmental temperature. The senor of the sensor array is quartz tuning fork non-contact temperature sensor based on the polymer line, with the high precision and the low cost and the simple manufacturing process. The system will use the Bayes estimation to fuse the measured temperature data the array get, and it overcomes that the precision is not high, and the sensitivity is limited now. The system has advantages of the fast response, the high precision, the high reliability, the low cost, and the system is easy to realize.

2. The Composition of the Sensor Array

2.1. The Structure and the Principle of the Quartz Temperature Sensor

The sensor is mainly composed of the quartz tuning fork and the polymer line attached to the quartz tuning fork. The experiments show that the sensitive component of the polymer line is N - isopropyl acryl amide that is most sensitive to temperature and is easy to get in life. Due to the resonance frequency of 32.768 kHz quartz tuning fork is low cost and good anti-jamming, the sensor selects the quartz tuning fork of 32.768KHz, 4 mm long, 0.25 mm wide, and 0.6 mm thickness, and bending vibration mode is chosen as the working mode of quartz tuning-fork temperature sensor, and chooses AT-cut as the thermal cutting type of the temperature sensor [7-11]. Its structure is shown as Figure 1.
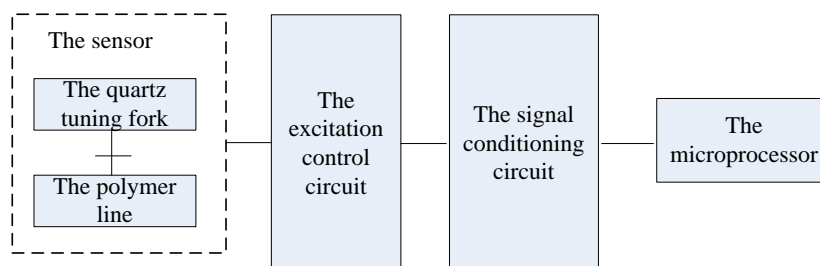

Figure 1. The Overall Structure Diagram of the Senor

The development of the polymer quartz tuning-fork temperature sensor is as follows: first of all, scrape off the shell of the quartz tuning fork; Then, drop N - isopropyl acrylamide $0.1 - 1 \mu L$ on the tuning fork arms using the optical microscope; Finally, dip a thick needle in the above solution, and pull the needle to the other arm of the tuning fork slowly, and notice that the operation must be done after the solution is completely dry. Repeat several times and form the polymer line. The dried polymer solution will solidify on the fork arms. The polymer line of quartz tuning fork sensor structure diagram is shown as Figure 2.
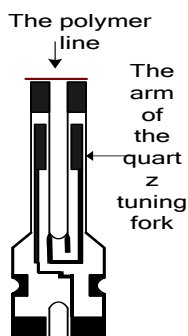

Figure 2. The Structure of the Sensor

The principle of the quartz tuning-fork temperature sensor based on the polymer line is putting the N - isopropyl acrylamide solution that is high sensitivity to temperature on the arms of the quartz tuning fork resonator that are relatively insensitive to the temperature. Making full use of its temperature-sensitive feature, operate alternating incentive in the quartz tuning fork resonator, to make the resonator work and the output frequency fixed. Because The change of the ambient temperature, N - isopropyl acryl amide heated drains off water and absorbs the water in the low temperature, like a resonant structure consisting of a spring and glue pot to drive the quartz tuning fork, and change the elastic coefficient of quartz tuning fork to deviate the output frequency of the resonator. Finally realizes the non-contact temperature measurement [10]. The relationship between environmental temperature and frequency deviation is as shown in (1).

$$\frac{\partial f}{\partial T} = \frac{\pi}{\sqrt{km}} \cdot \frac{\partial k}{\partial T}. \tag{1}$$

f is the output frequency, T is the environment temperature; k is modulus of elasticity, m is the quality of the quartz tuning for k. The spectrum diagram of the tuning fork quartz alone and the polymer line on the tuning fork is shown as Figure 3.
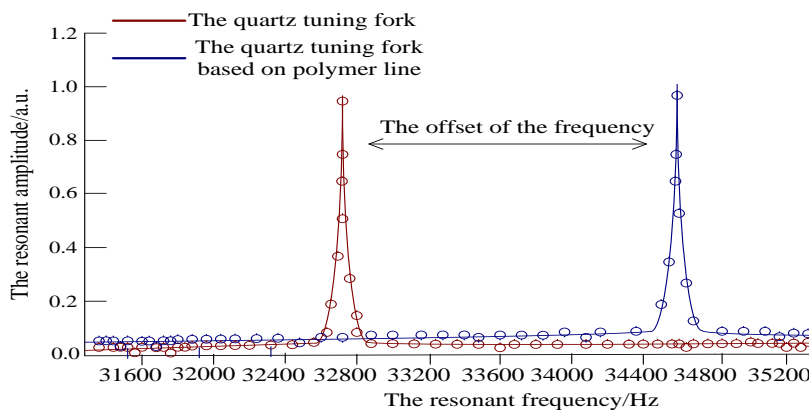

Figure 3. The Spectrum Figure of the Quartz Tuning Fork

The polymer line produces deformation due to changing of the ambient temperature, which leads to the quartz tuning fork resonator frequency offset. The red line represents frequency of the tuning fork alone in Figure 3, and its center frequency is 32716Hz, and the blue line represents is the frequency of the polymer line quartz tuning fork, and its center frequency is 34683Hz. The figure shows obviously that produce the frequency offset of the quartz tuning fork after put the polymer line on it. We can calculate the sensor temperature data using (1).

2.2. Design of the Sensor Array

Building the initial array needs to consider some necessary practical problems, like that the sensitivity and accuracy of the sensor array are required very high, and the temperature sensors used in the array are quartz tuning fork infrared temperature sensor based on polymer line, which is a senor of the high sensitivity, the good stability, the rapid response speed, so the sensor has the incomparable advantages.

According to the layout of the sensor array, the diamond grid can improve the sensor's perception and communication ability better, and the key is to ensure seamless detection in sensor networks.

To achieve the full coverage in the area of the sensor network, requires at least N nodes, and N can be given by the following (2):

$$N = \frac{F}{\delta} = \frac{F}{\frac{3\sqrt{3}}{2}r^2} \tag{2}$$

F is the area of the sensor area, $\delta = 3\sqrt{3}r^2/2$ is the network area of the each node, r is the detected range of the sensor. At the time of detect temperature, the sensor is placed on the vertice of the diamond grid. Measuring temperature based on the diamond grid achieves using a minimum number of sensors to detect the largest area finally.

The system of the sensor array is implemented based on the diamond grid, and has made some improvements. Three lozenge grids constitute a parallel quadrilateral layout, which the temperature measurement ranges are no overlap and each sensor's interference is small. At the same time, wrap it as a fixed precision infrared temperature measuring device to reduce dynamic measuring errors and the temperature measurement is more accurate and convenient. The deployment of the sensor array adopted by the system is shown as Figure 4.
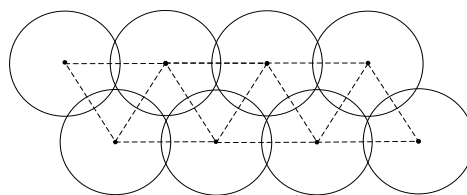

Figure 4. The Deployment of the Sensor Array

The circle in the figure center is the sensor nodes, and the layout is cross between rows and columns. The layout improves the static sensor deployment of the diamond to make eight nodes constitute the three diamond networks. Set up the 2 x 4 traditional sensor array and the new array shown in Figure 4 to measure the temperature, respectively and assume that the measured data obey the normal distribution. Two tests are shown as Figure 5 and Figure 6 respectively.
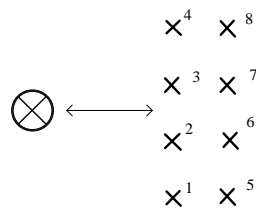
$$\times^4 \quad \times^8$$
$$\times^3 \quad \times^7$$
$$\otimes \longleftrightarrow$$
$$\times^2 \quad \times^6$$
$$\times^1 \quad \times^5$$

Figure 5. The Temperature Measurement of the Traditional Array

$$\times^4 \quad \times^8$$
$$\times^3 \quad \times^7$$
$$\otimes \longleftrightarrow$$
$$\times^2 \quad \times^6$$
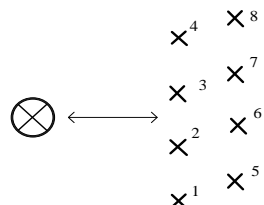$$\times^1 \quad \times^5$$

Figure 6. The Temperature Measurement of the Diamond Array

Two arrays measure temperature respectively and obtain the temperature. Use a confidence distance measure as the synergetic data to compare the alignment of two arrays by calculating the confidence matrix. Assume that the measured data of the sensor i and j is X_i and X_j respectively, and introduce the confidence distance measure according to the method of the compatibility matrix to reflect the deviation and the compatibility between the between two sensors. Equation (3) is the method of the d_{ij}.

$$\begin{cases} d_{ij}=erf\left[\dfrac{x_j-x_i}{\sqrt{2}\sigma_i}\right] \\ d_{ji}=erf\left[\dfrac{x_i-x_j}{\sqrt{2}\sigma_j}\right] \end{cases} \qquad (3)$$

$erf(\theta)$ is as the equation (4) and it is the error of the function,

$$erf(\theta)=\frac{2}{\pi}\int_0^{\theta} e^{-u^2}du \qquad (4)$$

The d_{ij} is the confidence distance measure between sensor I and sensor j. The d_{ij} is smaller, and then the measurement value between the two sensors is closer, and the deviation is smaller, the compatibility is better. The temperature data of the traditional sensor array as shown in Figure 5 is in Table 1.

Table 1. The Measurement Data of the Traditional Temperature Array

The serial number of the sensor	The temperature measurement data (°C)
1	37.20
2	37.43
3	37.45
4	37.40
5	37.05
6	37.35
7	37.37
8	37.30

The temperature measurement data of the diamond array as shown in Figure 6 is shown in Table 2:

Table 2. The Temperature Measurement Data of the Diamond Array

The serial number of the sensor	The temperature measurement data (°C)
1	37.20
2	37.43
3	37.45
4	37.40
5	37.34
6	37.38
7	37.42
8	37.36

Comparing the two groups of the experimental data, the value of sensor 1, 2, 3, 4, 5 in the Figure 5 is similar to the value of sensor 1, 2, 3, 4, 5 in the Figure 6, so we focus on comparing the integration degree of the sensor between the first column and the second column in two figures respectively. Calculated by the formula 5,the fusion matrix value of the sensor 5 and senor 1in Figure 5, and the fusion matrix value of the sensor 5 and senor 1in Figure 6 are: d_{51}=0.5199, d_{51}'=0.3714; At the same time, the fusion matrix value of senor 5 and senor 2,and senor 7 and senor 3,and senor 8 and senor 4 in two figures are: d_{62}=0.2164,d_{62}'=0.1367, d_{73}=0.2902, d_{73}'=0.0631, d_{84}=0.1882, d_{84}'=0.0626.The data measured show: $d_{51} > d_{51}$', $d_{62} > d_{62}$', $d_{73} > d_{73}$', $d_{84} > d_{84}$', Namely the sensor alignment of the two columns in Figure 6 is less than the sensor alignment of the two columns in Figure 5 significantly, and the compatibility of sensors in the Figure 6 is better than the compatibility of sensors shown in Figure 5 ,thus the effectiveness of the measurement data is higher and more reliable than the effectiveness of the traditional array. So the paper adopts the sensor array of the Figure 6.

The layout of the sensor array in this system is based on the diamond grid, and the temperature measuring surface between sensors is cross, and the overlap area of the temperature measurement is small, so avoid the small coverage of the traditional determinant array effectively and achieve the integrity of the source of the data, and make the follow-up data processing is simple relatively, and the results of the fused data are more accurate and reliable.

3. The Fusion of Data

The method of the data fusion adopted by the system is the algorithm based on Bayes estimation. The temperature measurement data using the diamond network sensor array is as shown in Table 1.

At first, determine valid data of the array, using the histogram method to remove the invalid data, and set the maximum value of X_{max} in the group, minimum value is X_{min}, the median is X_M. The sorted sensors measuring temperature value in Table 3:

Table 3. The Sorted Measuring Temperature Data

The serial number of the sensor	The temperature measurement data (°C)
1	37.20
2	37.34
3	37.36
4	37.38
5	37.40
6	37.42
7	37.43
8	37.45

Because the number of the data of the group is 8, and 8 is even, so X_M=($X_{(8/2)+1}$+$X_{8/2}$)/2,and calculate it: X_M=(37.38+37.40)/2 =37.39. The upper quartile F_0 is the median interval of the [X_M, X_{max}], and F_0= (37.42+37.43)/2=37.425；The lower quartile F_1 is the median interval of the [X_{min}, X_M], and F_1= (37.34+37.36)/2=37.35.The discrete

degree of quartile is dF= F_0- F_1, and calculate dF=0.075. The judgmental interval of the Invalid data is $|X_i - X_M| > \beta dF$, and β is 1,and that is $|X_i - X_M| > 0.075$,and the effective data are {37.34,37.36,37.38,37.40,37.42,37.43,37.45}.

Then use Bayes estimation to calculate the valid data. The estimation is in the moment method, and the maximum likelihood method and the total probability solution discuss the problem of the parameter estimation all under the condition that the unknown parameter $\boldsymbol{\theta}$ is as a random variable, if we can provide some additional information of the unknown parameters $\boldsymbol{\theta}$ in advance, which is good to estimate the parameters, and this is the basic ideas of Bayes estimation[11-13].

Definition 1 :(Bayes estimation) Set the parameter θ as a random variable in the total distribution function $F(x, \boldsymbol{\theta})$, and for any decision function $d(\xi_1,...,\xi_n)$ there is a decision function $d(\xi_1,...,\xi_n)$ to make the (5) right [14].

$$B(d^*) = \min_d(B(d)) \tag{5}$$

Then d^* is the estimator of Bayes of the $\boldsymbol{\theta}$, and $B(d)$ is called the risk of Bayes of the decision-making function $d(\xi_1,...,\xi_n)$.

Theorem 1: If the loss function is quadratic $L(\boldsymbol{\theta}, d) = \boldsymbol{\theta} - d(\xi_1,..., \xi_n)^2$, the estimator of Bayes of the$\boldsymbol{\theta}$is as the (6):

$$d(\xi_1,...,\xi_n) = E(\boldsymbol{\theta}\xi_1,...,\xi_n) = \int_\Omega^\boldsymbol{\theta} p(\boldsymbol{\theta}\xi_1,...,\xi_n)d\boldsymbol{\theta} \tag{6}$$

If want to calculate the estimator of Bayes of the$\boldsymbol{\theta}$, should calculate p ($\boldsymbol{\theta}\xi_1,...,\xi_n$) first[15].

To fusing the data of the temperature, eight sensors are measuring the temperature at the same time in the thesis, and the number of the fusion is 7, and the valid data are {37.34, 37.36, 37.38, 37.34, 37.36, 37.43, 37.45}.The equation is shown as (7).

$$p(\mu x_1, x_2,..., x_7) = \frac{p(\mu; x_1, x_2,..., x_7)}{p(; x_1, x_2,..., x_7)} \tag{7}$$

If μ obeys $N(\mu, \sigma_k^2)$, and x_k obeys $N(\mu_0, \sigma_0^2)$, and $\alpha = 1/p(x_1, x_2,..., x_7)$, and α has nothing to do with the constant μ , there is the (8):

$$p(\mu x_1,..., x_7) = \alpha \exp\left\{-\frac{1}{2}\sum_{k=1}^7 \left[\frac{x_k - \mu}{\sigma_k}\right]^2 - \frac{1}{2}\left[\frac{\mu - \mu_0}{\sigma_0}\right]^2\right\} \tag{8}$$

Compare the parameters of the (8) and (9):

$$\mu_N = \left[\sum_{k=1}^7 \frac{x_k}{\sigma_k^2} + \frac{\mu_0}{\sigma_0^2}\right] \bigg/ \left[\sum_{k=1}^7 \frac{1}{\sigma_k^2} + \frac{1}{\sigma_0^2}\right] \tag{9}$$

According to the equation (10), the estimator of Bayes of the μ is the $\hat{\mu}$:

$$\hat{\mu} = \int_\Omega \mu \frac{1}{\sqrt{2\pi}\sigma_N} \exp\left\{-\frac{1}{2}\left[\frac{\mu - \mu_N}{\sigma_N}\right]^2\right\} d\mu = \mu_N \tag{10}$$

The average in the group is $\mu_0 = x_1 + \ldots + x_7 / 7$, and $\mu_0 = 38.3971$, and $\sigma_0^2 = \frac{1}{7}\sum_{i=1}^{7}(x_i - \mu_0)^2$. Get the data followed, according to the formula $\sigma_i^2 = \sum_{i=1}^{i}(x_i - \mu_0)^2$:

$\sigma_1^2 = 0.00326041$; $\sigma_2^2 = 0.00463682$; $\sigma_3^2 = 0.00492923$; $\sigma_4^2 = 0.00493764$; $\sigma_5^2 = 0.00546205$; $\sigma_6^2 = 0.00654446$; $\sigma_7^2 = 0.00934287$; $\sigma_0^2 = 749.2344$.

There is the calculated result according to the (10): $\mu_N = 79265.4453/2119.9224 = 37.39072963$. So the data based on Bayes estimation is 37.39072963.

According to the serial number of the sensor in the table 2, calculate the fused data orderly, and the temperature measurement data of the sensor 1 after being fused is itself, and that is $\mu_{1N} = 37.34$. When sensor 2 and senor 1 are measuring temperature at the same time, estimate 37.34 and 37.43 using Bayes estimation, and $\mu_0 = 37.385$, $\sigma_0^2 = 0.002025$, and the data after being fused is $\mu_{2N} = 37.3763$; Increase the sensor to measure the temperature in turn, and calculate based on Bayes estimation, and the data is shown as (11).

$$\begin{cases} \mu_{3N} = 37375.1681/999.2723 = 37.4024 \\ \mu_{4N} = 62008.241932/1659.9556 = 37.4004 \\ \mu_{5N} = 59038.42258/1578.525 = 37.4010 \\ \mu_{6N} = 66791.7128/1785.8329 = 37.4009 \\ \mu_{7N} = 72253.8367/1933.06623 = 37.3778 \end{cases} \tag{11}$$

The temperature compared curve is shown as Figure 7 according to the above data:
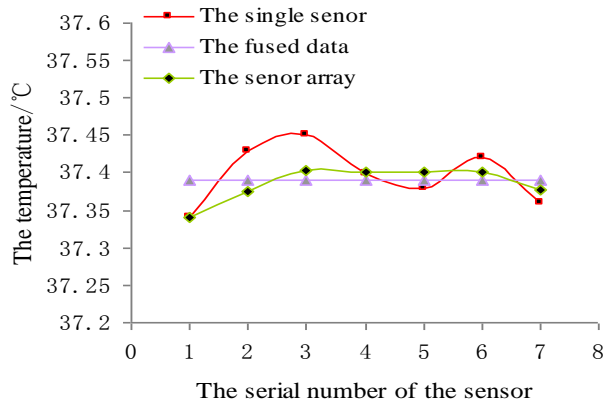

Figure 7. The Temperature Compared Curve

The square in the graph is the data measured by the single temperature sensor, and the diamond is the data measured by arrays and the triangle is the data fused by Bayes estimate. By the curve we can know that the data measured by the array fusion is obvious more stable and accurate and smaller errors than the data measured by the single sensor. In the experiments, using the frequency meter to display the temperature corresponding to the frequency, the experimental temperature interval is $\Delta T = 37.45 - 26.45 = 10°C$, and the corresponding frequency offset is $\Delta f = 38998.21 - 38965.14 = 33.07Hz$. The sensitivity of the sensor array is $71.5 \times 10^{-6}/°C$.

4. Conclusions

The system is based on temperature sensor array of the polymer line quartz tuning fork. The quartz tuning-fork temperature sensor based on the polymer line has a very broad practical prospect in various fields with the high sensitivity, the high accuracy, the good stability, and the common raw materials. The diamond grid array increases the control range of the sensor array and realizes the seamless coverage of the sensor temperature measurement range. Use the method of eliminating error on the data process to obtain the valid data and calculate the fusion data using Bayes theorem. Diamond temperature sensor array is proved more accurate and sensitive and stable than the single sensor by experiment, the measurement precision of the system is 0.2 ℃, the sensitivity of the system is71.5 x 10-6 / ℃.

Acknowledgment

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