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Study on Temperature Recognition of Thermal Paint Based on Color Camera

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Abstract. As a temperature-sensing material, the thermal paint will show different colors at different temperatures, so the temperature of the thermal paint can be judged by observing the color. It is an efficient way to identify the color of the thermal paint by the color image, so the calibration of the color camera is very important. The main work of this paper is to calibrate a color industrial camera and compare our proposed method with several commonly used methods. Finally, it is concluded that the proposed method combining BP neural network and maximum entropy estimation works best.

1. Introduction

In the experimental study of aero-engine, it is very important to measure the wall temperature of hot-end components (including stationary parts and rotating parts), such as turbine disk, turbine blade, casing, flame tube, power cylinder heat insulation screen and so on. Thermal paint is an essential tool for accurate analysis of high temperature materials and maximum heat resistance [1].

Thermal paint is a kind of special temperature sensing coating used to measure the surface temperature and distribution of the attached object by using the color change of the coating [2].

The principle is that when the coating is heated to a certain temperature, some physical or chemical changes occur in the heat-sensitive pigment in the coating, resulting in changes in molecular structure and molecular morphology, and even decomposition into other substances. As a result, the color of the coating film is changed to indicate the temperature.

The commonly used manual interpretation method [3] to judge the temperature by the color of thermal paint has some problems such as large analysis error, low efficiency, difficulty in quantitative analysis and so on. However, it is an efficient and convenient way to identify the color of thermal paint to judge its temperature based on color camera. Therefore, it is required that the color calibration of the color camera used to identify the color of thermal paint should be very accurate.

In this paper, a color industrial camera is calibrated by the combination of BP neural network and maximum entropy estimation (CBPNNMEE). Comparisons between the proposed method and several common calibration methods are also done. The results show that the combination of BP neural network and maximum entropy estimation is the best.

2. Color Camera Color Calibration Method

In this paper, the imaging measurement is used in the experiment. Color images of samples are taken with a color camera, and the RGB values of the samples are extracted. In fact, the RGB values measured by color cameras produced by different manufacturers are not the same, and even the products produced by the same manufacturer may not be consistent. If the RGB values measured by color cameras are not accurate, it is difficult to ensure accuracy in the process of color measurement and evaluation. Therefore, it is necessary to establish the mapping relationship between the RGB values measured by color cameras and the standard color tristimulus values (XYZ), which is the calibration process of color cameras. There are three common calibration methods, PAL algorithm, three-dimension Look-Up-Table (3D-LUT) algorithm and BP neural network algorithm.

2.1. PAL Algorithm

In this method, the mapping between the RGB color space of color camera and the standard CIE XYZ color space is processed in a linear way, that is, there exists the following matrix conversion relationship between them.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M * \begin{bmatrix} R_0 \\ G_0 \\ B_0 \end{bmatrix} \tag{1}$$

M is PAL color conversion matrix which is known. There is a specific conversion relationship between (R,G,B) and (R_0,G_0,B_0). The specific steps are as follows:

First, the RGB value of the camera response of the whiteboard is measured, and its camera tristimulus value X_t, Y_t, Z_t is calculated according to the PAL color conversion formula, and then the correction coefficient of the camera system can be obtained, as follows:

$$k_x = \frac{X_r}{X_t}, k_y = \frac{Y_r}{Y_t}, k_z = \frac{Z_r}{Z_t} \tag{2}$$

X_r,Y_r,Z_r is the CIE standard chromaticity value of the whiteboard.

When measuring the actual samples, the camera tristimulus values of the samples can be obtained following the same steps above, and then according to the correction coefficient, the actual tristimulus values of the samples can also be obtained.

2.2. Three-Dimension Look-Up-Table Algorithm

This algorithm realizes the spatial mapping of data by establishing a point-to-point comparison table. It uses several points in 3D space to estimate a new point. In general, the steps to realize the 3D-LUT are as follows: first, measure a large number of data pairs as data nodes to construct the lookup table, then look for the points participating in interpolation, and finally realize the data interpolation of non-nodes. The emphasis of the method is the establishment of the lookup table and the interpolation method.

When the data nodes in the three-dimensional space are uniformly distributed, we can divide the three-dimensional space into several cubes through the uniformly distributed data. At this time, the interpolation algorithms include cube interpolation, tetrahedral interpolation and so on. However, in general, the obtained data nodes are not uniformly distributed, and the Euclidean distance between the interpolation point and the node is usually adopted in interpolation method. The lookup table algorithm mentioned below is this method. Now that the tristimulus values of various color samples can be determined in PAL algorithm, maybe they have a large error. But, on this basis, we can establish the mapping relationship between these tristimulus values and the standard measurement tristimulus values, and establish the database. The method is as follows:

$$\mathrm{A} = \sum_{i=1}^{n} W_i * B_i \tag{3}$$

$$W_i = \frac{\frac{1}{r_i^2}}{\sum_{i=1}^{n} \frac{1}{r_i^2}} \tag{4}$$

r_i is the distance between the interpolation point and the neighboring nodes. B_i is the corresponding point of the neighboring nodes in the target space.

2.2.1. Maximum entropy estimation [4]. For each input point, the maximum entropy estimation can reconstruct the output points linearly in the target space by calculating the weights of the sampled points within its local neighborhood. In the color space, each input point is assumed to be in a convex hull composed of sampled points, which means that the weight sum is one. Therefore, the problem of solving weights is equivalent to determining the most possible allocation problem under the constraint of known average expectation. Under the constraint of known expectation, the most probable distribution of the maximum entropy is the distribution of the maximum probability. Therefore, the maximum entropy estimation weight is the maximum possible weight. The maximum entropy estimation algorithm is as follows:

Let the sampled points be the pairs$\{x, f(x)\}$. Given a new point *y*, *f(y)* is estimated by using the maximum entropy estimation.

Step 1 Taking the input point *y* as the center, the adjacent *k* points are selected to form a convex hull.

Step 2 Calculate the weights w_i:

$$\max(-\sum_{i\in k} w_i * lnw_i) \tag{5}$$

subject to the constraints:

$$\sum_{i\in k} w_i * x_i = y \tag{6}$$

$$\sum_{i\in k} w_i = 1 \tag{7}$$

$$w_i \geq 0 \tag{8}$$

Step 3 Form the estimate *f(y)* as:

$$f(y) = \sum_{i\in k} w_i * f(x_i) \tag{9}$$

2.3. BP Neural Network Algorithm

The error back propagation neural network has the ability to realize nonlinear mapping. By measuring an appropriate amount of samples as a training set and adjusting the training parameters of the network, the mapping relationship between input and output can be obtained. Typical diagram is as follows:

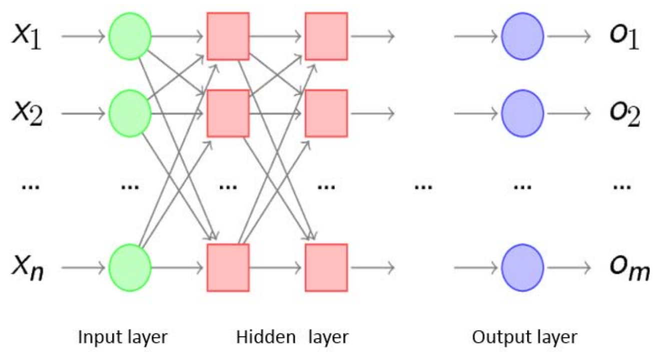

Figure 1. Neural network model.

For this paper, the input layer is the camera RGB value of the samples, and the output layer is the standard XYZ value of the samples. The structure of BP neural network is 3-10-10-10-3.

2.4. CBPNNMEE Algorithm

Regardless of the calibration method, the more training samples, the higher the calibration accuracy. However, in practice, the training samples are usually limited, which requires the use of limited samples to improve the calibration accuracy as much as possible. In this paper, a method combining BP neural network with maximum entropy estimation is proposed. Firstly, a certain number of training sample sets are measured, and the corresponding mapping relationship between samples is determined by BP neural network. Then the RGB color space of the camera is divided into 27*27*27 data nodes to expand the samples. The trained network is used to determine the values of the target space corresponding to 27*27*27 data nodes. Finally, the maximum entropy estimation method is used as the interpolation method to obtain the values of the target space corresponding to the unknown points.

3. Calibration Experiment

3.1. Experimental Instrument
Spectral radiometer (PR715), SG color card, NCS color card, light box, camera, whiteboard

3.2. Experimental Method and Process
- Place the SG color card in the light box and turn on the D65 light source.
- Place the camera at the distance of the light box 50cm, and the geometric conditions of lighting and measurement are 45°/ 0°.
- Turn on the computer and connect to the PR715.
- Turn on the camera imaging software, adjust the camera aperture, exposure time and other parameters to make the image clear, the RGB value of the whiteboard part is around 230.
- Shoot the color card with the camera and store pictures.
- Replace SG color card with NCS color card, use the camera to shoot the color card, store the picture.
- Each color block of the two color cards is measured by PR715 in the same measurement environment as the camera, and the XYZ data obtained is reserved.

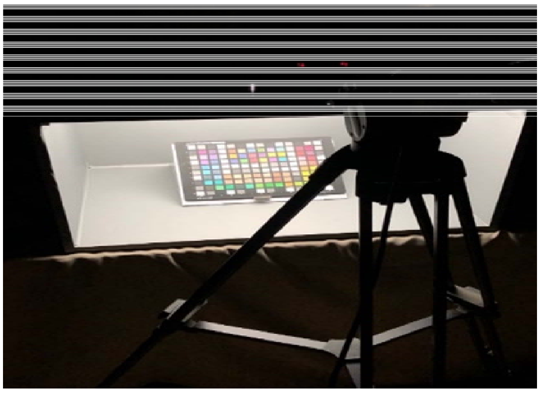

Figure 2. Shooting of SG color card.

3.3. Data Processing and Analysis
The obtained images are processed by the image processing software, and the RGB values of each color block are extracted. And then, the correspondence table based on the SG color card is established.

Figure 3. Picture of SG color card.

Based on the calibration methods mentioned above, the corresponding XYZ values of 900 NCS blocks selected from NCS color card are calculated. The color differences between the XYZ values measured by PR715 and the XYZ values calculated are calculated in CIE1976 L*a*b* uniform color space. The results can be seen in Table 1.

Table 1. Comparison of color differences between calibration methods.

Error	Mean	Maximum
PAL	18.06	29.31
LUT	4.85	11.13
BP neural network	2.68	6.91
Maximum Entropy Estimation	3.85	6.54
CBPNNMEE	1.86	5.93

As can be seen from the table, PAL calculation method has the worst calibration accuracy, which indicates that the linearity between the RGB value of this camera and the standard XYZ value is not high. The performance of the lookup table based on Euclidean distance is not bad, and this method is adequate for the camera with low precision requirements. The BP neural network method and the maximum entropy estimation perform well, indicating that these two methods have good ability for nonlinear mapping. The method of combining BP neural network with the maximum entropy estimation has the best performance, which shows that the strong nonlinear mapping ability and sufficient samples play a key role in improving the calibration accuracy.

4. Temperature Recognition of Thermal Paint [5]

4.1. Fit the Color Temperature Characteristic Curve Function of Thermal Paint

Color-temperature database is established by photographing the thermal paint samples with the calibrated color camera. The color is represented by *L, a, b*. Regardless of the correlation between the *L, a* and *b* components, and assuming that the values of the respective color components are functions of temperature *t*, denoted as *L(t), a(t), b(t)*. The color temperature characteristic curve function of thermal paint is fitted with a cubic spline interpolation method.

4.2. Temperature Recognition Algorithm

For the temperature of the unknown point, the Euclidean distance between it and any point on the color temperature characteristic curve of thermal paint is calculated in the CIE1976 L*a*b* color space. Denote the Euclidean distance by ΔE.

$$\Delta \mathrm{E} = [(L(t) - L)^2 + (a(t) - a)^2 + (b(t) - b)^2]^{1/2} \tag{10}$$

The above formula is solved in the temperature measuring range of t thermal paint to find the *t* value that minimizes the ΔE. The *t* value is the corresponding temperature value on the thermal paint picture.

5. Conclusion

There is a corresponding relationship between the temperature of thermal paint and the color. The color of the thermal paint can be obtained through imaging, and then the temperature can be known. Therefore, this paper focuses on the camera color calibration, and the proposed method combining BP neural network with maximum entropy estimation has satisfactory results. In the future work, it is necessary to study new techniques and methods to improve the accuracy of camera color calibration and temperature identification of thermal paint.

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