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Method to Remove the Effect of Atmosphere and Ambient Radiation on Colorimetric Temperature Measurement

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Traditional colorimetric temperature measurement methods usually make use of visible light and near-infrared band. They commonly yields high accuracy in measuring close targets at high temperature, however low accuracy in measuring distant targets at medium or low temperature. Given the limitations of traditional methods, an infrared colorimetric temperature measurement method which takes the effect of atmospheric parameters and environment radiation into account is proposed. A colorimetric temperature measurement model which environmental radiation is taken into account is derived. In addition, a MWIR camera and two band-pass filters are used for colorimetric temperature measurement to verify the proposed method. The experiment results shows that, absolute error and relative error of temperature measurement using the method considering atmospheric parameters and environment radiation are less than 4°C and 6.7%, respectively; moreover the radiometry error of the gray body is less than 10%, which demonstrates that the proposed method is valid for measuring distant targets at medium or low temperature.

1. Introduction

Temperature is one of the major characteristics of materials. Since the measurement of temperature plays an important role in many fields. Radiation thermometry is a non-contact temperature measurement method based on the Planck's Law, which can measure the temperature of target over a wide range and has no influence on the temperature field of target; it is characterized by highly real-time, sensitive, safe and reliable performance. Therefore, it is widely adopted in adverse environment. As a non-contact temperature measurement method, colorimetric temperature measurement method has all the advantages of Radiation thermometry; in addition, colorimetric temperature measurement method can measure the true temperature of targets with unknown emissivity, which overcomes the difficulty of emissivity measurement during measuring temperature.

At present, colorimetric temperature measurement method has been widely used in national defense, military, scientific research and industrial production, Vinay and Prabhu (2013) reported an experimental investigation to obtain temperature and emissivity of different materials, which was performed to measure the local temperature using the colorimetric method with a charge coupled device camera in the visible region. Zhang et al (2010) used the colorimetric method to reconstruct the multi-dimensional, inhomogeneous combustion temperature distribution inside industrial through flame radiation images from the ratio of the two monochromatic intensity distributions. Francesco et al (2001) proposed a two-dimensional soot diagnostic technique based on the well-known bichromatic pyrometry of two-dimensional soot diagnostic techniques, used to measure the temperature field of soot, and the practicability of it was proved by typical combustion environment experiments. All the applications mentioned above made use of visible light and near-infrared band. Due to the measured targets are in a short distance and have a high temperature, the atmosphere and environmental radiation on the radiation transfer path have lesser impact on the temperature measurement. However, Ward Small IV et al (1998) reported a bichromatic mid-infrared thermometer with a hollow glass optical fiber; the ambient radiation would produce a noticeable output of system when the target is cold enough, which must be subtracted from the measured signal. Therefore, the impacts of environmental radiation on targets must be taken into consideration in colorimetric temperature measurement, and when measuring distant targets, the influence of atmosphere can neither be ignored.

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To solve the problems above, Julia r. Dupuis et al (2006) presented a new approach to measure temperature of target over different standoff ranges in varying atmospheric conditions by carefully selecting the spectral pass-bands of the two images generated from uncooled micro-bolometer focal plane arrays. Ren Yan et al (2014) indicated that the precision of temperature measurement was limited by atmospheric attenuation and radiation when measuring the temperature of target in the atmosphere; they used the piecewise linear method to fit the colorimetric temperature measurement curve, and then got a high precision of temperature measurement. These studies have made certain achievements in their fields, respectively. However the measured targets were mainly high temperature targets. Therefore, the influence of atmosphere and environment must be taken into account in measuring medium or low temperature targets.

This paper analyzes the principle of colorimetric temperature measurement and proves the feasibility of colorimetric temperature measurement using two band-pass filters and medium-wave infrared imaging system, this paper proposes a new colorimetric temperature measurement method by taking atmospheric and environmental factors into account and derives the calibration and measurement models of colorimetric method. In the end, an experimental platform of colorimetric temperature measurement based on a medium-wave infrared imaging system was established, and experiments of temperature measurement were conducted in the laboratory. The precision of temperature measurement was high, laying the foundation for the application of colorimetric temperature measurement method in photoelectric measurement systems.

2. Principles of colorimetric temperature measurement

Colorimetric temperature measurement method is to measure the true temperature of objects by establishing functional relations between the radiance ratio of target in different wavelengths and the temperature. In practice, band-pass filters are usually used to obtain the radiation of targets in different bands (Joseph J. T. et al., 2012). To measure a target at the temperature of Tt, the equivalent radiance can be expressed as:

$$L_t = \frac{\varepsilon}{\pi}\int_{\Delta\lambda_N} \tau_{atm}(\lambda)\times\tau_{opt}(\lambda)\times R_{det}(\lambda)\times R_{fil}(\lambda)\times L_b(\lambda, T_t)\,d\lambda \tag{1}$$

where $\Delta\lambda_N$ refers to the pass-band of filter; ε refers to the emissivity of target in $\Delta\lambda_N$, $\tau_{atm}(\lambda)$ refers to the atmospheric spectral transmittance in $\Delta\lambda_N$, $\tau_{opt}(\lambda)$ refers to the spectral transmittance of optical lens in $\Delta\lambda_N$, $R_{det}(\lambda)$ refers to the spectral response of detector, $R_{fil}(\lambda)$ refers to the spectral transmittance of filter, and $L_b(\lambda,T_b)$ refers to the blackbody radiance at the temperature T_b.

For close targets, the atmospheric absorption can be ignored and the spectral transmittance of optical lens can be seen as a constant τ_{opt} , so the radiance ratio $R(T)$ of two pass-bands of filters can be represented by:

$$R(T) = \frac{L_{t1}}{L_{t2}} = \frac{\dfrac{\varepsilon_1\tau_{opt}}{\pi}\int_{\Delta\lambda_{N1}} R_{det}(\lambda)R_{fil1}(\lambda)L_b(\lambda, T_t)\,d\lambda}{\dfrac{\varepsilon_2\tau_{opt}}{\pi}\int_{\Delta\lambda_{N2}} R_{det}(\lambda)R_{fil2}(\lambda)L_b(\lambda, T_t)\,d\lambda} \tag{2}$$

In Eq(2), all the definitions of physical quantities are in agreement with the previous equations; subscript 1 and 2 are sequence numbers of filters. Assuming that the emissivity of targets remains the same in the wave band $\Delta\lambda_{N1}$ and $\Delta\lambda_{N2}$, by use of Eq(2), the emissivity and the transmittance of optical systems can be removed, and *R(T)-T* curve will be obtained; then the true temperature of targets will be inversed using the radiance ratio of targets in two wavebands.

3. Colorimetric temperature measurement method considering impacts of atmosphere and ambient radiation

3.1 Calibration model

In this paper, the colorimetric temperature measurement system adopts near-extended-source method, which means the blackbody is put before the optical lens. In order to reduce the influence of atmospheric path radiation, absorption, scattering and background radiation on the detecting path on calibration, the blackbody is put as closely as possible to the infrared system, which is shown in Figure 1a.

In consideration of the influences of filters, the radiance $L_{BN}(T_b)$ of the blackbody at the temperature of T_b can be represented by:

$$L_{BN}(T_b) = \tau_{opt}\int_{\Delta\lambda_N} R_{det}(\lambda)R_{fil}(\lambda)L_b(\lambda, T_b)\,d\lambda \tag{3}$$

Within the linear range of mid-wave infrared detectors, the gray value output h of the pixel of the detector in the colorimetric temperature measurement system can be described by:

$$h = G_N \times L_{BN}\left(\lambda, T_b\right) + B_N \quad (4)$$

where G_N refers to the response of the colorimetric temperature measurement system towards the equivalent radiance of targets, B_N refers to the offset of the calibration model, including the gray values output caused by the stray radiation inside the infrared system (e.g. radiation of optics lens and mechanical structure) and the detector itself (e.g. dark current), as well as the radiation of filters.

In the single-band calibration of the colorimetric temperature measurement system, the response G_N and the offset B_N of single-band calibration curve were obtained by fitting the radiance $L_{BN}(T_b)$ and the corresponding gray value h by linear least squares method, then the single-band calibration of the colorimetric temperature measurement experimental system was accomplished.

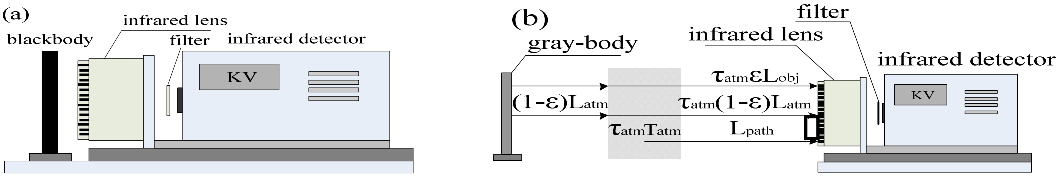

Figure 1: (a) Schematic diagram of calibration, (b) Measurement model of colorimetric temperature measurement system

3.2 Measurement model and colorimetric calibration curve

According to the assumption of colorimetric method, during the colorimetric temperature measurement, the target is considered as gray body, whose emissivity is ε, which will be affected by ambient environment. Therefore, what the colorimetric temperature measurement system receives is not only the radiation of targets, but also includes the environment radiation reflected from the surface of targets and the atmospheric radiation. The measurement model is shown in Figure 1b.

In Figure 1b, τ_{atm} refers to the atmospheric transmissivity; T_{atm} refers to the ambient temperature; L_{obj} refers to the radiance of targets considering the spectral transmittance of filters and the spectral response of infrared detectors. The radiation received by the system includes: the radiation of targets reduced by the atmosphere is $\tau_{atm}\varepsilon L_{obj}$, the reflected ambient radiation is $(1-\varepsilon)L_{atm}$, and the atmospheric path radiation is L_{path}. τ_{atm} and L_{path} can be obtained by distant blackbody calibration experiment using colorimetric temperature measurement system; L_{atm} is the ambient radiation on the detecting path; which can be seen as the blackbody radiation of ambient temperature, and obtained by the Planck's Law (Carlos R. et al, 2005).

According to what has been mentioned above, the total radiance received by the system can be represented by:

$$L_{tot} = \tau_{atm}\varepsilon L_{obj} + L_{path} + \left(1-\varepsilon\right)L_{atm} \quad (7)$$

Then L_{tot} is substituted into the calibration Eq(4), the measure equations of two different wave bands can be described as:

$$h_1 = G_{N1}\tau_{atm1}\varepsilon_1 L_{obj1} + G_{N1}L_{path1} + G_{N1}\left(1-\varepsilon_1\right)L_{atm1} + B_{N1} \quad (8)$$

$$h_2 = G_{N2}\tau_{atm2}\varepsilon_2 L_{obj2} + G_{N2}L_{path2} + G_{N2}\left(1-\varepsilon_2\right)L_{atm2} + B_{N2} \quad (9)$$

Where all the variables are in agreement with the previous equations, subscripts 1 and 2 are sequence numbers of filters.

According the previous assumption that the emissivity of targets remains the same in the pass bands of the filters, measurement formula can be obtained by rearranging Eq(8) and Eq(9) as:

$$\frac{\alpha_2 L_{obj2} - \beta_2}{\alpha_1 L_{obj1} - \beta_1} = \frac{h_2 - B_{N2} - G_{N2}L_{path2} - \beta_2}{h_1 - B_{N1} - G_{N1}L_{path1} - \beta_1} \quad (10)$$

Where $\alpha_1 = G_{N1}\tau_{atm}$, $\alpha_2 = G_{N2}\tau_{atm2}$, $\beta_2 = G_{N1}L_{atm1}$, $\beta_1 = G_{N2}L_{atm2}$, and all the parameters were known. According to Eq(10), the blackbody radiance ratio of the two filters can be defined as:

$$R\left(T\right) = \frac{\alpha_2 L_{obj2} - \beta_2}{\alpha_1 L_{obj1} - \beta_1} \quad (11)$$

Before temperature measurement, according to the single-band calibration of the colorimetric temperature measurement system, and Eq(11), then the calibration curve *R(T)-T* can be obtained by calculating the radiance ratio *R(T)* in two pass-bands of filters. During the temperature measurement, the measurement images of targets are collected respectively, the true radiance ratio can be calculated by substituting the gray value of images and corresponding physical quantities into right of Eq(11), which can be substituted into *R(T)-T* curve to calculate the actual temperature of targets.

4. Experiment and results

4.1 Experiment platform of colorimetric temperature measurement

In this paper, the colorimetric temperature measurement experimental system is based on a medium-wave infrared camera, including the medium-wave infrared detector, optics lens, two band-pass infrared interference filter, black body and the device stimulating gray-body. The infrared detector operates in 3.7~4.8 um waveband, with a 14-bit digital output, and the focal length of the optical lens is 100mm, and F/#=2. The filters are fixed on a rotating between the detector and the optical lens. To prevent blocking transfer path of radiation, the filters closely stick to the front of the detector, hence all the radiation getting through the lens can reach the detector.
According to the theoretical analysis and experiments, with considering the spectral response of the detector, experimental system adopts two infrared interference band-pass filters made by Spectrogon Corp, whose central wavelengths are 4520nm and 4665nm, and the bandwidths are 220nm and 240nm, respectively. Therefore, the enough radiation can reach to our system. The blackbody used in the experiment is a SR800 high accuracy extended area blackbody made by CISYSTEMS Corp in Israel, which has a 100mmX100mm size and exhibits high effective emissivity (about 0.97), and its temperature accuracy is 0.01 °C over the temperature range of 0 °C to125 °C.
To verify the performance of colorimetric temperature measurement method proposed in this paper, a homemade gray-body stimulating device shown in Figure 2(a) is suggested in the experiments, which is manufactured by fixing a homemade emissivity plate on the constant temperature heating platform made by Polish Corp. The thermal resistances are used for heating in the device. The heating area size of the device is 200mmX200mm, and its temperature accuracy is 0.2°C over the temperature range of 20 to 400 °C. To validate the temperature measured, the thermocouples were internally installed in the center of the heating platform.

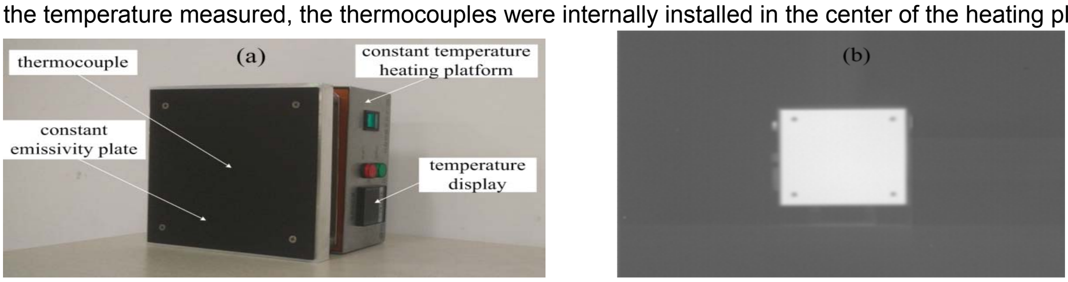

Figure 2 Gray-body and its measurement image (a) real diagram of gray-body; (b) measurement image of gray-body

4.2 Experiment procedure

This experiment was conducted in the laboratory. Before the experiment, the integration time of the colorimetric temperature measurement system was selected as 0.66ms. After that, the single-band calibrations in different pass-bands were carried out respectively. The diagram of calibration is shown in Figure 3a.

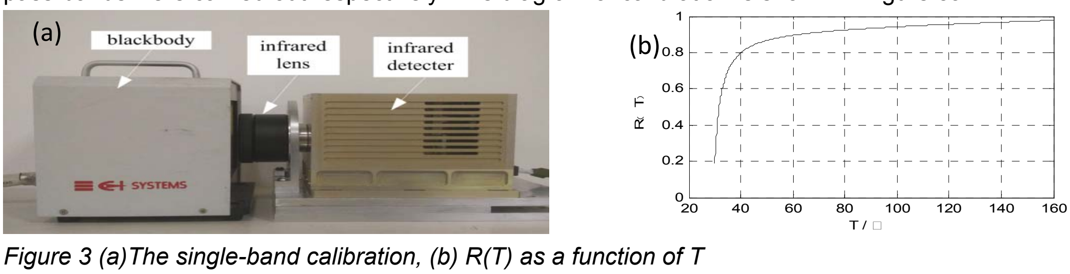

Figure 3 (a)The single-band calibration, (b) R(T) as a function of T

The calibration image of the blackbody was collected from 30°C to 120°C (interval 10 °C) in different wavebands. By fitting the curve between gray value of the calibration image and the radiance of the blackbody, calibration results are obtained. Based on the results of the single-band calibrations and Eq(10), the *R(T)-T* curve shown in Figure 3b was established.

In the Measurement experiment, the integration time was also selected as 0.66ms, and the target was set 9m from the whole system. The measurement images of the target at 40°C, 80°C, 100°C, 120°C, and 150°C in different wave bands were collected at the ambient temperature of 22.9°C, respectively. In order to obtain the accurate atmospheric transmissivity and the path radiation on the detecting path in different wave bands, the reference blackbody was put near the target for the long-distance calibration. Then the transmissivity and the path radiation of atmosphere can be calculated by comparing the results of long-distance calibration with that of short-distance calibration. The calculated results of parameters are shown in Table 1

Table 1: The atmospheric parameters and ambient radiance

Central wavelength	Atmosphere transmittance	Path radiance $/\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{sr}^{-1}$	Ambient radiance $/\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{sr}^{-1}$
4520nm	0.7903	0.0911	0.3043
4665nm	0.8499	0.0796	0.3202

As seen in Figure 2(b), the measurement image of the target was uniform in 4665nm band. Due to the infrared detector we used has a wide linear range, the gray value of target obtained in measurement experiments is considered in the linear range of that approximately. The temperature measurement region was selected in the center of image of the target, which are 49 pixelX49 pixels size. The real radiance ratio *R* was obtained by substituting the data in Table 1 and the gray values of temperature measurement region into Eq(10). Combining *R(T)-T* curve with measurement ratio, the temperature of target can be gained, then. The average temperature of temperature measurement region was regarded as the real temperature of the measured target, and the temperature measured by the thermocouple was regarded as the true temperature of the target. And then, the results are shown in Table 2

Table 2 Measurement results of proposed method

Temperature /℃	Average of R	Measured temperature/℃	Relative error of temperature /%	Radiance in middle infrared		
				Radiance/ $\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{sr}^{-1}$	Measured radiance $/\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{sr}^{-1}$	Error of radiance /%
40	0.8187	42.03	5.08	2.0819	2.23	6.96
80	0.9189	82.85	3.56	6.8168	7.34	7.74
100	0.9418	101.04	1.04	11.2393	11.52	2.49
120	0.9568	123.32	2.77	17.6331	18.92	7.30
150	0.9726	151.12	0.75	32.0498	32.72	2.09

The effect of atmosphere is not taken into consideration in the traditional method, when measuring close target at high temperature. However, the effect of atmospheric transmissivity should be considered for the long-distance target in the traditional method, without taking path radiation and ambient reflected radiation into account. Using the same experiment data in this paper, to compare the temperature measurement accuracy of the traditional colorimetric temperature measurement method and that of the method suggested in this paper, The results the traditional method is shown in Table 3.

Table 3 Measurement results of traditional method

Temperature /℃	Average of R	Measured temperature/℃	Relative error of temperature /%	Radiance in middle Infrared		
				Radiance/ $\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{sr}^{-1}$	Measured radiance $/\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{sr}^{-1}$	Error of radiance /%
40	0.9601	34.32	-14.20	2.0819	1.72	-17.53
80	1.0030	82.45	3.06	6.8168	7.27	6.63
100	1.0219	111.54	-88.46	11.2393	0.74	-93.46
120	1.0350	133.15	10.96	17.6331	23.16	31.33
150	1.0472	155.42	3.61	32.0499	35.39	10.43

4.3 Analysis of results

Table 2 and Table 3 respectively stand for the results obtained by the method proposed in this paper and the traditional colorimetric temperature measurement method. It can be seen from Table 2 that by using the method proposed in this paper, the absolute error is less than 4°C and the relative error is less than 6%, which represents a high accuracy of temperature measurement; the relative error of the medium-wave radiance is less than 8%. It is clear that the higher the temperature of the target is, the more accurate the measurement is. Table 3 stands for the results obtained by the traditional colorimetric temperature measurement method. It can be seen that the temperature calculated is very different from the true temperature. At the temperature of 100°C, the absolute error of temperature and the relative error of medium-wave radiance reach 11 °C and 33%, respectively. It is mainly because the effect of the ambient radiation reflected from the target and the path radiation are not taken into account in the calculation of real radiance ratio, which leads to a bigger ratio and a bigger calculated result.

It can be seen from the analysis above that although the effect of atmospheric absorption is considered in the traditional colorimetric method, the accuracy of temperature measurement remains low, especially in the measurement of the low temperature target. In other words, the atmospheric path radiation and the environmental radiation have great influence on the accuracy of measurement, when measuring the low temperature target. However, the method proposed in this paper simultaneously considers the influence of atmosphere and ambient radiation; it is not only applicable for high temperature target measurement, but also accurate to measure medium or low temperature targets. The maximal temperature of gray-body only reached 150 ℃in temperature measurement experiment, however, the maximal measurement temperature can be raised by selecting less integral time or using other detector.

5. Conclusions

Long-distance temperature measurement is affected by the emissivity of targets and atmospheric parameters. The traditional colorimetric temperature measurement method can eliminate the influence of emissivity, however atmospheric parameters and the environmental radiation are not taken into consideration, which limits the accuracy of measuring target at medium or low temperature. This paper proposed a colorimetric temperature measurement method which considers the effect of atmosphere and environment, and establishes a colorimetric temperature measurement and calibration model with environmental factors taken into account. Accurate temperature measurement of medium or low temperature targets is therefore achieved. The experiment results demonstrates that, the colorimetric temperature measurement method suggested in this paper can effectively reduce the influence of atmosphere and environment on colorimetric temperature measurement, and it has higher accuracy in measuring medium or low temperature targets, compared with the traditional method.

The proposed colorimetric temperature measurement method can be used to measure the targets in different environments and distances. In the temperature monitoring process of industrial production, when the monitoring distance or the environment changes, target temperature measurement can be achieved again only by re-measuring the atmospheric parameters and the environment temperature using the colorimetric temperature measurement method considering atmosphere and ambient radiation. Therefore, the method proposed in this paper is more flexible facing changes of measuring distance. In terms of military use, this method can be used in the target radiation measurement system. Theoretically, the true temperature of targets can be obtained, and it may have certain significance in the study of raising the accuracy of measuring the radiation characteristics of infrared targets with low emissivity.

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