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Measurement performance of an optical CCD-based pyrometer system

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ABSTRACT

The measurement performance of a CCD-based pyrometer system using a three-color method was evaluated for scientific and engineering metrology. The relationships between the system parameters (exposure time and sensor gain) and the intensity measurements in an integrating sphere experiment were determined for a specific CCD sensor. The pyrometer system uses the three-color method based on the intensity ratio without geometry calibrations. The field measurement characteristics and the effectiveness of coupling the three-color channels were investigated in terms of the temperature measurement uniformity, temperature sensitivity and temperature range of the pyrometer system in standard blackbody tests. The results showed that the temperature non-uniformity is not proportional to the intensity non-uniformity and is in the range of 0.13–2.14%. The relative temperature sensitivities of intensity ratios for different channel combinations are different, which may provide a way to improve the measurement results. The temperature range bandwidth for object with a non-uniform temperature distribution varies from 190 to 270 K for this specific CCD-based pyrometer. The performance evaluation conclusions for the system with this specific CCD sensor are general and applicable for pyrometer systems using other CCD sensors.

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1. Introduction

Optical radiation pyrometry, the determination of the temperature of an object based on its luminosity caused by thermal self-radiation, is an effective and practical method for measuring combustion temperatures or surface temperatures. In recent years, optical pyrometers have been built with a charge coupled device (CCD) for temperature distribution measurements through optical visualization [1–8]. A CCD is a light-sensitive integrated circuit that stores and displays the data for an image in such a way that each pixel in the image is converted into an electrical charge. CCDs are used in the astronomical telescopes, scanners, machine vision system, optical character recognition and meteorology. The availability of CCD sensors conveniently provides temperature field measurements which overcomes the shortcoming of traditional spot pyrometers only detecting several points.

Existing CCD-based pyrometer systems based on the multi-color method use various means to separate the measurement wavelengths/wavebands with single CCD or multiple CCDs. The former is more advantageous due to the simple system design. In a single CCD system, images for different colors may be sequentially formed on the same monochrome sensor array through a beam splitting/filtering assembly with narrow-band interference filters [2–4] or they can be simultaneously obtained from a color sensor array with a mosaic pixel filter (for example, an *R-G-B* Bayer filter) [6–8]. The method using narrow-band interference filters corresponds to multi-color pyrometry with wavelength measurements, while that using an *R-G-B* Bayer mosaic pixel filter is looked upon as multi-color pyrometry with waveband measurements. If *R-G-B* waveband measurements are simplified as three effective wavelengths measurements, it will cause great error even though the conversion relationship is calibrated with blackbody experiments.

Previous research on CCD-based pyrometer systems has mainly focused on two approaches to calculate the temperatures. One approach is to beforehand calibrate the system to determine the relationship between the radiation intensity and the corresponding sensor output using the same geometric parameters for the system and the measured object [4]. This relationship is only suitable for the measurements at the same geometric condition. Once the condition is changed, the calibration process needs to be undertaken again. The other approach is to utilize the radiation intensity ratio of different wavelengths/wavebands as a relative intensity. The geometric factor, Φ (Eq. (1)), is eliminated through the ratio processing (Eq. (10)) and it avoids the calibrations for the geometry condition [6,7]. The measurement uncertainties of these two approaches were theoretically evaluated by Fu et al. [9]. The correlation theory and other aspects of CCD-based pyrometry applications have been analyzed in many references [10–19].

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Although optical pyrometers based on color CCDs have been applied in research studies of high-temperature measurement with promising results, there are few commercially available CCD-based multi-color pyrometers for temperature field measurements in engineering applications. Some technology issues are still worth further studying. The measurement ability of the CCD-based pyrometers using the multi-color method has not received sufficient attention or been scientifically analyzed in the literature. In applications of CCD sensor as a scientific temperature metrology device, it is necessary to evaluate the system measurement performance, including the measurement uncertainty [20,21], system parameters, measurement range and measurement sensitivity. The image processing and CCD-sensor characteristics are generally related to the system parameters (exposure time, sensor gain, etc.), but the quantitative relationships between these parameters and the intensity/temperature measurements are not clear. This analysis is based on a three-color pyrometer system using a color CCD to evaluate the system performance for scientific and engineering metrology as a function of the system parameters, measurement uniformity, measurement sensitivity and measurement range. The coupling characteristics of the three-color channels in the pyrometer system, based on the intensity ratios, cause the analysis of the measurement performance to be much different from analyses of traditional and commercial single/dual-channel pyrometer systems, arising from the intensity ratio analyses of more channels. In addition, performance analyses of field measurements with CCD-based pyrometers also differ from analyses of other systems measuring only several points. The analysis presented in this paper provides a valuable description of the performance of CCD-based pyrometers using the multi-color method to make such systems more practical for scientific and engineering applications.

2. Calibration of CCD-based pyrometer system

The design of a CCD-based pyrometer system is shown in Fig. 1. The color CCD is the key part of the optical pyrometer system, with its characteristics determining the measurement performance of the optical pyrometer system. The system data processing procedure is shown in Fig. 2. The light rays are focused on the CCD focal plane and then translated into electronic signals. The system applies gains and then does an A/D conversion to get the digital output signals. The pixel values of the recorded CCD frame image are the outputs of the array of micro-sensors. The instrument sensor parameters, including the image LUT (look-up-table), aperture, shutter, global gain and $R/G/B$ gain, are the important adjustable quantities in the CCD-based pyrometer system. These parameters control the intensity measurements of the micro-sensors which affect the temperature measurements.

The equation relating the spectral irradiation to the pixel output of the frame image is:

$$C_i = \eta\kappa_i\left(\Phi\cdot\frac{\Delta t}{F^2}\int_{\lambda_s}^{\lambda_e} s_i(\lambda)\cdot I(\lambda)\,d\lambda + n_i\right), \quad i=R,G,B \tag{1}$$

Where C_i is the pixel digital value with non-dimension in channel i, obtained by A/D conversion. For a 8 bit output, this value range is from 0 to 255. $I(\lambda)$ is the spectral distribution of the irradiance reaching the CCD sensor per unit time at wavelength λ, W m^{-2} sr^{-1} μm^{-1}; $s_i(\lambda)$ is the spectral sensitivity for the combinations of lens/image-optics/color-filter/sensor in channel i; Φ is a geometric factor that is a function of the radiation attenuation, observation distance, observation angle and lens properties; Δt is the exposure time, s; F is f-number of the aperture; n_i is the dark noise in channel i and may be estimated by capturing frame images with the lens cap on the pyrometer; (λ_s,λ_e) are the system wavelength range, nm; η is the zooming coefficient relative with the global gain; and κ_i is the zooming coefficient relative to the $R/G/B$ channel gain. In Eq. (1), different channels (i=R, G, B) correspond to different micro-sensors with different spectral response distributions in the CCD-based system. Therefore, the image pixel values (C_R, C_G, C_B) may be looked upon as three channels of system outputs.

Defining $E_i = \Phi/F^2(\int_{\lambda_s}^{\lambda_e} s_i(\lambda)I(\lambda)d\lambda)$:

$$C_i = \eta\kappa_i(\Delta t E_i + n_i), \quad i=R,G,B \tag{2}$$

When η=1 and κ_i=1, $C_{i,0}=\Delta t\cdot E_i+n_i$.

This research used a pyrometer system based on the IMC 147FT CCD camera with the ICX285AL chip (progressive scanning, 1,450,000 pixels 1392(H) × 1036(V), cell size 6.45 × 6.45 μm, 12 bit data depth, S/N ratio > 56 dB, 20 FPS at maximum resolution), for the following analysis. The spectral sensitivity curves $s_i(\lambda)$ of IMC 147FT CCD camera may be determined by spectrum experiments [7]. Here only a brief description of the measurement

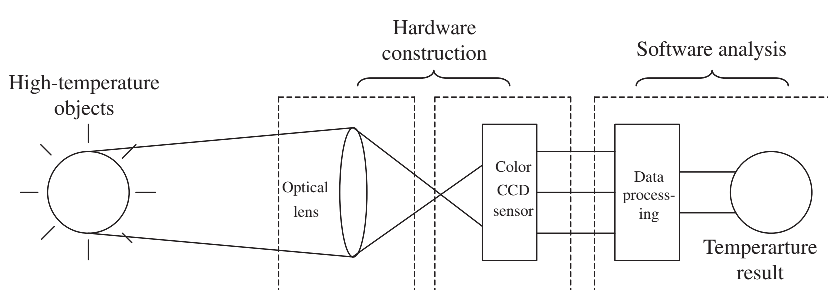

Fig. 1. Design of a CCD-based pyrometer system.

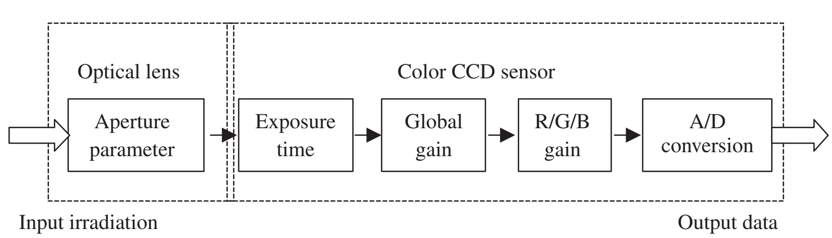

Fig. 2. System data processing.

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