Design and implementation of high-speed multiwavelength pyrometry measurement system based on CMOS image sensor

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The detonation temperature is measured both theoretically and experimentally by means of a complementary metal oxide semiconductors (CMOS) image sensor. An experimental system of multiwavelength temperature measurement based on CMOS image sensing technology is designed and realized. The instant spectral information of each moment is captured by row with the CMOS image sensor, depending on the unique characteristic of its rolling shutter. With the use of multiwavelength temperature measurement theory and by fitting spectrum emissivity through the regressive least square method, the color temperature of the detonation whose temperature is variable can be obtained continuously. The system is calibrated by measuring the standard spectrum of the laser. In our system, four time temperatures are measured within 10-μs detonation. Results show that the system has a higher measuring accuracy and speed, and can be applied in high-speed spectral information collection and storage during the detonation.

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In recent years, the accuracy and stability of noncontact thermometry have been significantly improved. Many methods that focus mainly on measuring the radiant, bright, and multiwavelength temperatures have been proposed. Among them, the multiwavelength pyrometer has been considered the most accurate and the least dependent on the emissivity of target. However, the method reveals obvious shortcomings of the pyrometer[1−7], such as the determination of the surface emissivity of target by many aspects such as temperature, roughness of target, and selected wavelength for measuring.

Numerous devices that can realize noncontact high-temperature measurements have been found in the market; however, often, their use has been restricted to the observation of objects of known emissivity. If the body to be controlled behaves as a blackbody, all the devices inferring the true temperature from the body radiation are accurate and reliable. In contrast, when it exhibits a behavior different from the blackbody, the emissivity compensations need to be conducted.

Therefore, in cases where the emissivity is known, the spectral system with a single wavelength is preferentially used. For a graybody with constant emissivity in a narrow bandwidth, a bicolor system is more likely utilized[8]. For the other cases, assumptions regarding the emissivity variations with the wavelength and the temperature have been ascertained, and multispectral systems that are mixes between spectral and multispectral systems have been built and used. Unfortunately, most of the proposed systems are unable to measure the explosion processes simultaneously and could not be used in real-time data processing. To overcome this problem, a real-time multispectral imaging system based on complementary metal oxide semiconductors (CMOS) image sensor is presented in this letter. We have carefully characterized the system and discussed its applications in vision control.

Multiwavelength techniques that can simultaneously perform true temperature and emissivity without using any auxiliary means are important in the field of radiation thermometry. Noncontact temperature measurements are based on the detection and analysis of thermal radiations emitted by an object. The radiation of an object is governed by Planck's radiation law:

$$E(\lambda,T)=\varepsilon(\lambda,T)C_1\lambda^{-5}\exp(-C_2/\lambda T-1)^{-1},\qquad(1)$$

where $E(\lambda,T)$ is the spectral radiation intensity (unit:W/m^3); λ is the wavelength (unit:m); ε is the emissivity; G is the instrument constant; T is the absolute temperature (unit: K); C_1 and C_2 are the radiation constants, with the value of 3.742×10^{-16} W·m^2 and 1.4388×10^{-2} W·K), respectively.

The wavelength and temperature concerned in this study range from 0.6 to 0.8 μm, and from 1000 to 2200 K, respectively. Because $\lambda T \ll C_2$ within these ranges, Planck's radiation law can be replaced by Wien's radiation law:

$$E(\lambda,T)=\varepsilon(\lambda,T)C_1\lambda^{-5}\exp(-C_2/\lambda T).\qquad(2)$$

If a multiwavelength pyrometer has N channels, the output V_i at the ith channel can be written as

$$V_i=G_i\varepsilon(\lambda_i,T)C_1\lambda_i^{-5}\exp(-C_2/\lambda_i T).\qquad(3)$$

At the reference blackbody temperature $T_{\rm b}$, the output $V_{\rm b}$, at the ith channel is

$$V_{\rm b}=G_iC_1\lambda_i^{-5}\exp(-C_2/\lambda_i T_{\rm b}).\qquad(4)$$

Combining Eqs. (4) and (5) leads to

$$\frac{V_{\rm i}}{V_{\rm b}} = \varepsilon(\lambda_i, T)\exp(-C_2/\lambda_i T)\exp(-C_2/\lambda_i T_{\rm b}). \qquad (5)$$

Knowing the value of G_i is unnecessary, because G_i was canceled out in Eq. (5). The relationship between emissivity and wavelength is represented as a polynomial,

$$\ln\varepsilon(\lambda, T) = \sum_{i=0}^{m} a_{i+1}\lambda^i, \qquad (6)$$

where $m \le n-2$. If $Y_i = \lambda_i \ln(\frac{V_i}{V_{\rm b}}) - \frac{C_2}{T_{\rm b}}, a_0 = -\frac{C_2}{T}, X_{1,i} = \lambda_i, \cdots, X_{m,i} = \lambda_i^m$, we can obtain

$$Y_i = a_0 + a_1 X_{1,i} + \cdots + a_m X_{m,i},$$
$$(i = 1, 2, \cdots, n; m \le n-2). \qquad (7)$$

The system consists of an optical system, CMOS image sensors, a high-speed image acquisition card, and the spectral data analysis software, as shown in Fig. 1. Radiation emitted by the investigated object is collected by the optical system and subsequently transmitted through band pass filters to the detectors. The electrical signal is amplified and converted to digital form. Finally, using the proposed technique, the emissivity (or temperature) of the measured object is calculated.

The light-splitting system with lens is shown in Fig. 2. L_1, L_2, and L_3 compose the three-lens system which can make the incident light energy to focus on the slit D; and P is a grating aimed at dispersing the incident light from short-wave to long-wave at the beginning of the zero order. The imaging is shown on back focal plane by L_4 based on the grating equation

$$d\sin\alpha = k\lambda, \quad (k = 0, \pm1, \pm2\cdots), \qquad (8)$$

where d is the grating constant, λ is the wavelength of incident light, k is the diffraction order, and α is the diffraction angle. For a given grating constant d, diffraction stripes are at different wavelengths, but of the same order. In addition, the dominant maximum does not overlap outside of the zero order. Moreover, they are dispersed from shortwave to longwave at the beginning of the zero order to the left and right sides. The dominant maximal stripe is the sharp bright line in the diffraction image. Therefore, when lights with different wavelength components travel to the grating, all the wavelength components can be detected on the back focal plane. These dominant maximal lines are arranged based on the light wavelength. The larger is the diffraction order k, the clearer is the diffraction effect; however, the energy is decreased. In addition, the slit width must be adjusted not only to generate diffraction spectra, but also to meet the need of CMOS image sensor luminance. In the process of measuring the spectral line, the image can be dynamically revised according to the computer output information.

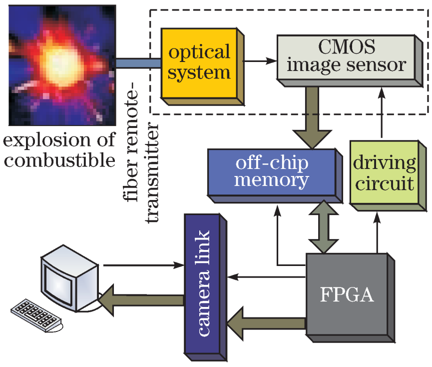

Fig. 1. Experimental setup for a multiwavelength system.

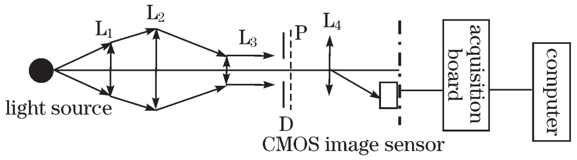

Fig. 2. Optical diagram of the multiwavelength pyrometer.

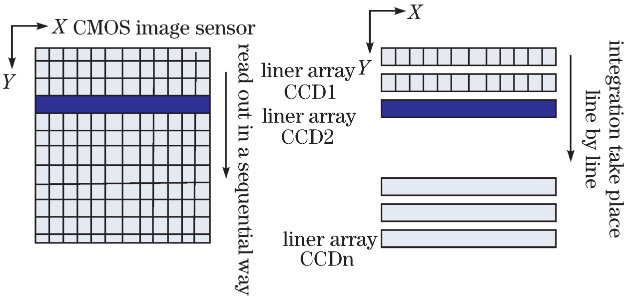

Fig. 3. CMOS image sensor and CCD linear array.

Figure 3 shows that at the rolling shutter mode planar array, the CMOS image sensor has equal interval. The instant spectrum information of each moment in each row is captured by the CMOS image sensor, depending on the unique characteristic of its rolling shutter. After fitting of spectrum emissivity using the regressive least square method, the variable color temperature of the illuminant is obtained continuously, according to the multiwavelength temperature measuring theory.

Different heat treatment processes operated on Delphi and multithread programming was performed on the proposed system. The CMOS sensor was connected to an DVR Express CL-160 frame grabber, and temperature measurements were realized. Experiments show that the card was successfully applied to the high-speed plane array CMOS imaging data collection. Storage data recovery through software analysis shows that derived data are accurate, without throwing frames.

The main task for calibration is to establish the relationship between $E(\lambda)$ and $g(\lambda)$. Here, $E(\lambda)$ is the light illumination that enters CMOS image sensor through the optical system, and $g(\lambda)$ is the gray value corresponding to the pixel of spectral image obtained from CMOS image sensor. In real measurement, each pixel value of the sampled digital image was converted to the corresponding irradiance produced in the process of detonation with this quantitative relationship. Finally, the detonation temperature was computed by fitting the obtained value.

If the spectral dispersion is even, we can approximate that a linear relationship between the wavelength and the

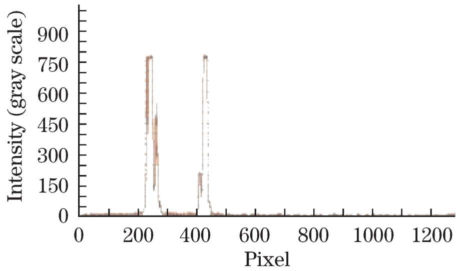

Fig. 4. Calibration of CMOS image sensor spectral curve.

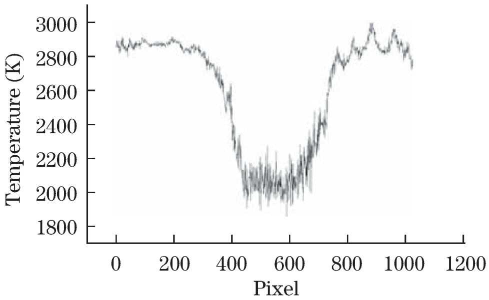

Fig. 5. Halide tungsten light temperature variation curve.

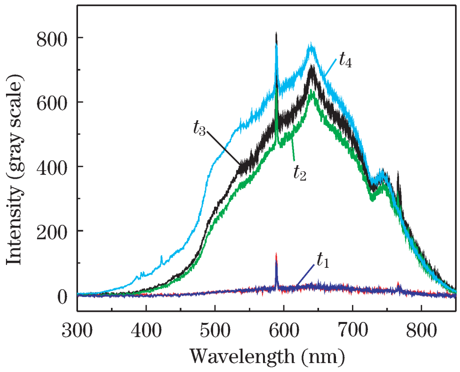

Fig. 6. Dynamic spectra of detonation radiation. $t_1 - t_4$ denote the four different time when we get the spectra.

CMOS pixel position exists. With x as the pixel position, the relationship is described as

$$\lambda(x) = a + bx. \tag{9}$$

Lasers with wavelengths of 630 and 532 nm were utilized for calibration in the experiment. The spectral curves corresponding to these two lasers on CMOS are shown in Fig. 4.

The 630 nm red light spectral line corresponds to the 240 pixel, and the 532 nm corresponds to the 420 pixel. With the two groups of data and Eq. (9), we obtain

$$\lambda(x) = 760.667 - 0.544x. \tag{10}$$

In the proposed application, CMOS image sensor was used to assess the temperature of the target. Figure 5 shows the experimental result of halogen obtained from bright to dark to bright spectral image. In the experiment, nitro-methane with different dilution explosive spectra was measured by this facility. Consecutive spectra within visible light region were obtained in the process of explosion, and subsequently transmitted to the computer for processing. Figure 6 shows four different explosion spectra within 10 μs in one explosion experiment. Through the comparison to the standard material value of nitro-methane detonation temperature, it can provide accurate, reliable detonation temperature.

All the uncertainties and errors were characterized for spectral temperature measurements (one wavelength) and for multiwavelength temperature measurements. A CMOS image sensor can sometimes be unsteady; thus, grey-level variations over a certain period for each CMOS image sensor were determined and represented as plus or minus one unit independent from its original value. To compensate for the slight variations (spatial and temporal) of the blackbody radiation, the effective grey level was calculated in a window with a size identical to that of a single-spot high-precision commercial optical pyrometer. The measurements were taken at ten different times (time evolution of the blackbody). The recorded grey-level variations were found to be negligible (less than half a unit).

In the actual use of the pyrometer, an uncertainty arises from aligning the pyrometer with the radiance source whose temperature is to be measured. In the temperature measurement, an additional uncertainty is present because of the combined effect of noise from the electronics and digitization by the analog-to-digital converter. This uncertainty was determined by calculating the standard deviation of individual digitized sample from the mean of a hundred samples when the pyrometer was focused on a steady radiance source. The standard deviation was found to be independent of radiance, which indicates that the uncertainty in temperature because of the noise and digitization increased rapidly with decreasing temperature.

In conclusion, a novel transient multiwavelength pyrometer system has been tested for the online continuous measurement of the temperature distribution on the detonation. Using all the optical parameters of the existing experimental system, the spectral range is from 250 to 750 nm, and the spectral resolution of the focal plane of the CMOS image sensor is 0.544 nm. Based on the multiwavelength illumination intensity among visible light spectra, standard color temperature light calibration, and multiwavelength color temperature regression analysis arithmetic, the system has successfully obtained the temperature of detonation and the temperature variation curve with time.

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