Thermography of inner surfaces of high-temperature industrial facilities

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Abstract. Thermography of inner surfaces of high-temperature facilities is an important task of industrial non-destructive testing. Existing methods operating in the visible wavelength range require the spectral scanning during the image acquisition to determine the distribution of temperature across the field of view. The infrared imaging techniques require specific lenses and image sensors. In this paper, we propose a method for remote determination of the spatial temperature distribution that is not limited by the mentioned restrictions. It is based on the use of an image sensor with a mosaic spectral filter array installed on it. This paper presents the layout of the prototype and the possibility of its practical application demonstrated in laboratory conditions.

1. Introduction

Various industrial technological processes, high-temperature synthesis of materials and other specific tasks require measuring the spatial distribution of temperature over the surface of controlled objects [1–5]. Since the infrared thermal imaging techniques are not compatible with the imaging devices operating in the visible wavelength range, they require the implementation of separate thermographic cameras. Therefore, methods implementing spectrum measurement of thermal radiation and its comparison with the theoretical Planck thermal radiation curve to determine the temperature of a sample are of interest. Since conventional spectrometers with a single-element radiation detector allow measuring only the value averaged over the field of view [6, 7], it is proposed to use spectral imaging methods to obtain the spatial temperature distribution.

There are various methods of measuring the temperature distribution over the facility surface. Measurement setups based on multichannel optical systems using separate optical paths to form images at several wavelengths simultaneously [8] are not widespread due to complexity of alignment and bulkiness. Systems based on mechanically switched spectral filters [9, 10] provide a small number of fixed spectral channels and low operational speed, and the presence of moving parts reduces the reliability of these devices.

Another method for measuring the spatial temperature distribution of samples involves spectral narrow-band filtering of radiation utilizing acousto-optic tunable filters (AOTFs). This method does not require any optical components movement to perform spectral scanning. In AOTFs spectral tuning is carried out by changing the frequency of the ultrasonic wave excited in the acousto-optic cell. AOTFs provide a wide operating spectral range and high spectral resolution. An ability to obtain a large number (up to several hundred) of spectral channels in a wide range of wavelengths allows...
getting higher measurement accuracy [11]. The arbitrary tuning of the filter allows one to acquire digital images in all of the required spectral bands. The spectral distributions of thermal radiation corresponding to each image pixel are determined using the obtained array of spectral images. The temperature and emissivity are calculated by the two-parameter fitting of the measured spectral distributions to the Planck’s curve. Since AOTF-based spectral imaging devices acquire spectral images by sequential tuning of the acousto-optical filter, the presence of the time delay between single narrow-band images limits the application of this method for measurements of fast processes and moving samples.

In this paper, we demonstrate the thermal imaging approach based on the simultaneous acquisition of several spectral images using image sensor with a mosaic spectral filter array, free of drawbacks inherent in the methods mentioned above.

2. Experimental setup and results
To determine the sample spatial temperature distribution we propose the use of the multispectral camera (Silios CMS series) based on the CMOS image sensor with a mosaic spectral filter array installed on it and an optical coupling system (SpaceCom JF50M, focal length is 50 mm) (figure 1). Each pixel of the used image sensor consists of 8 spectral subpixels with narrow-band filters (central wavelengths are 561 nm, 595 nm, 637 nm, 672 nm, 722 nm, 757 nm, 799 nm and 836 nm) and one wideband subpixel with neutral filter. Thus, the acquired image has 8 spectral channels and 1 wideband channel. The temperature at each point of the object is calculated by digital processing of spectral images with respect to the preliminary calibration data.

For experimental study we acquired the image series of heated furnace shown in figure 1. Two metal samples were chosen for the experiment. Samples were placed in a muffle chamber of furnace capable of heating up to 1100 °C. The samples were located at a distance of 500 mm from the camera lens. A blackbody calibration source was used for a preliminary temperature calibration (The Mikron M360 blackbody calibration source, temperature range from 50 to 1100 °C, emissivity ε = 0.995 ±0.0005). The images of the furnace chamber were acquired within 10 seconds after the muffle furnace door opening. The main purpose of the experiment was the demonstration of the ability to obtain images of high-heated objects and to calculate the temperature distributions. The temperature in the furnace was determined by the built-in sensor with a measurement error of 1°C. The temperature distribution on the surface of the samples was calculated using the Planck blackbody equation. In this paper, the simplified temperature calculation method was used (for details, see [12]).

Figure 1. The multispectral image acquiring process using a camera with a mosaic spectral filter array. 1 – copper sample; 2 – titanium sample.
The criteria of the sample choice are supposed to meet the following conditions. At first, the emissivity of the samples should be different for each sample and should be known a priori. Also, the samples should have flat and smooth surface free of oxides. Samples should withstand heating to high temperatures (more than 1000 degrees Celsius) without melting. According to these criteria the two samples shown in figure 2 were chosen.

Figure 2. Samples located in the muffle furnace and an example of calculated temperature distribution.

Figure 3. The calculated temperature distributions in the whole field of view (upper images) and across the selected pixel rows (H) and pixel columns (V) of the images acquired at 3 seconds (H1, V1, black curves) and 4 seconds (H2, V2, red curves) after opening the furnace door.
The titanium plate dimensions were 112×53×8 mm. The copper washer was 14 mm thick and 40 mm in diameter. The edge of the washer was cut for the safe and convenient alignment in the furnace. The melting point is 1668 °C for titanium and 1085 °C for copper. In order to maintain the temperature lower than the melting point, the maximum temperature of the muffle furnace for the experiment was 970 °C.

During the experiment, the furnace was heated to the temperature of 970 °C and then the furnace door was opened, and the multispectral images acquisition started. The calculated temperature distributions across the samples’ surfaces are shown in figure 3. In common practice, it is assumed that the emissivity is constant over the surface [2]. The emissivity value was assigned equal to the used blackbody calibration source (ε = 0.995) for these calculations. As the door opening initiated the intensive cooling of the samples and furnace inner surfaces, the later images indicate lower temperatures.

To compare the calculated temperature values with the indications of the built-in temperature sensor of the furnace, the measurements without cooling down were carried out. The multispectral image series was acquired through the peephole into the furnace door in order to maintain the stable temperature of the samples during the experiment. The example of temperature distribution calculated for one of the images obtained through the peephole is shown in figure 4. The border between the copper washer and the titanium plate surfaces can be seen in the central part of the calculated distribution.

![Figure 4](image-url)

Figure 4. The calculated temperature distribution in the whole field of view (left image) and across the selected pixel column (right image) obtained with the furnace door closed.

The results obtained for the dynamic process of sample cooling and for the stable temperature (with the furnace door being opened and closed, respectively) demonstrate the ability of the real-time remote thermal imaging provided by the described multispectral camera.

3. Conclusion
The described device prototype based on a multispectral camera provides simultaneous 8 narrow-band image acquisition with a high operation speed, limited only by the exposure time of the image sensor. The device is compact and free of moving parts. Experimental studies showed that the proposed setup can be used to determine the spatial temperature distribution over the surface of the object. The spatial resolution of the device was determined by image sensor pixel size and number of pixels, the number of spectral channels used in the mosaic spectral filter array and the lens magnification.
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