A novel approach to control gray level of image invariant during near infrared thermography

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Abstract:

Kinematic and thermal field measurements can provide rich information in the field of thermo-mechanics of materials and structures (e.g., constitutive model identification, fatigue behavior investigation, cracking detection, etc.). Up to now, silicon based sensor cameras (CCD and CMOS) have been widely used to perform in situ observation of the kinematic field on the material surfaces, mainly thanks to image correlation or interferometry. Thermal fields are usually obtained thanks to dedicated Infrared Cameras. Nevertheless, the acquirement of thermal fields using a silicon based sensor visible camera is possible and suitable for application at high temperature. In this study, a low-cost, high-resolution and contactless field measurement protocol is proposed to in-situ observe temperature distribution. Actually, silicon based sensor visible cameras are also sensitive in the near infrared spectral band (0.7-1.1 µm). In this spectral range, a temperature evolution readily results in a modification of the gray level obtained with the camera. It is usually considered as issues on the acquired images (saturation or poor dynamic range of gray levels) for visible acquisitions. Then adjust the exposure time of the camera with temperature evolution is a suitable method to maintain the gray level of image constant. In this work, we propose an approach to precisely and continuously adjust the exposure time to get a constant gray level of images whatever the temperature evolution. Black body experiments have been conducted to verify the approach.

Keywords: Black body; Silicon based camera; Radiometric model; Near infrared measurement

1 Introduction

Measuring precisely temperature distribution of an object undergoing thermal cycle is very important and meaningful. Many techniques have been developed for measuring temperature, e.g., thermocouple [1], thermistor [2], resistance temperature detector [3], pyrometer [4] and infrared thermography [5-7], etc. Among these methods, infrared thermography operating by infrared camera is a non-contact technology which has been widely applied in laboratory researches. Infrared thermography possesses several advantages: (1) no disturbance of the target surface to be measured; (2) high speed response; (3) possibility to measure the target objects which can be small, fragile, dangerous, and so on.

Nevertheless, the traditional infrared camera operating in middle infrared spectral ranges (e.g., 3-5 μm or 8-12 μm) has some essential problems. Firstly, the disturbance radiation from the surrounding objects to the target object is necessary to be measured, but the corresponding corrections are difficult because it depends on the surface states of objects; Secondly, most of time infrared thermography required a uniform surface with a homogeneous and even constant emissivity. However, for most of natural or artificial objects, their surfaces are non-homogeneous, thus these measurements are difficult with infrared thermography cameras. To avoid these two main disadvantages mentioned above, it is effective to operate in lower spectral ranges (near infrared spectral ranges). Teyssieux et al. [8] proposed that maintaining the surface emissivity constant, the disturbance radiation from surrounding objects is slight and can be negligible when the wavelength is inferior to 2 μm. But the influence of disturbance radiation from surrounding objects is obvious when the wavelength is superior to 2 μm. Their study indicated that the influence of disturbance radiation from surrounding objects can be ignored by applying lower spectral ranges. Rotrou et al. [9] studied the measurement of thermal field of an object with non-homogeneous emissivity by both infrared camera operating in the spectral ranges of 8-12 μm and a silicon-based camera operating in the spectral ranges of 0.7-1.1 μm, and the results showed that an accurate thermal field can be obtained by using silicon-based cameras with a lower spectral ranges, while the large errors will appear by using infrared cameras.

The cameras equipped with the silicon detectors, are not only operating in the visible bands (0.4-0.7 μm), but also operating in near infrared bands (0.7-1.1 μm). Thus, for high temperature applications, the visible cameras are good candidates to measure temperature fields. Meanwhile, the infrared cameras are expensive, fragile and low resolution due to the limited optical diffraction resulted from the application of the longer spectral ranges. Compared with infrared cameras, the silicon-based cameras are low-cost, low noise, durable and high resolution.

Although the silicon based cameras have so many advantages over the infrared cameras to realize the measurement of temperature field, a main disadvantage of near infrared thermography by using silicon based cameras is that, in the near infrared spectral range, the luminance (gray level in this study) increases faster with temperature evolution than in the infrared spectral range. Orteu et al [10] give the following example: in the near infrared spectral range (1 μm) the ratio of the luminance between 300℃ and 1000℃ is about one million, whereas in the long-wave infrared spectral range (10 μm) the ratio is only five.

The fast variation in luminance with temperature evolution readily leads to poor quality even bad images (oversaturation or poor dynamic range of gray levels), further resulting in the bad measurement of temperature field, therefore limiting its application to measure the temperature field.

In this study we propose an approach based on Planck's law to precisely and continuously adjust automatically the exposure time to get a constant gray level of images whatever is the temperature evolution.

2 Approach of controlling gray level invariant

2.1 Relationships among exposure time, temperature and gray level

Black body (RCN 1200 N1 manufactured by HGH) experiments were conducted at different exposure times and temperatures. A CMOS camera (Viewworks VC-12MC) with 4096 × 3072 pixels, mounted with a lens (Nikon ED) was used to measure the gray level of image taken from black body experiments. Fig. 1 shows an example of image acquired by camera and the rectangle region is the region of interest to be studied. Fig. 2 shows the gray level of images acquired at various temperatures from 790 to 910°C with a constant exposure time of 7 ms and 3 ms, respectively. It is apparent that the gray level of image increases fast with the increasing of temperature. The relationship between exposure time and gray level of image at the fixed temperature of 850°C is shown in Fig. 3. The results show that the relationship between gray level of image acquired is a linear function which is not dependent of the temperature

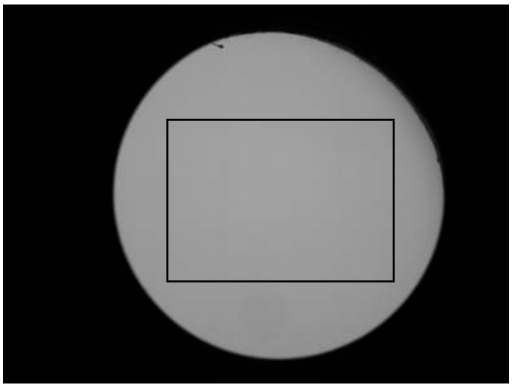

Fig. 1: An example of image acquired by camera and the region of interest.

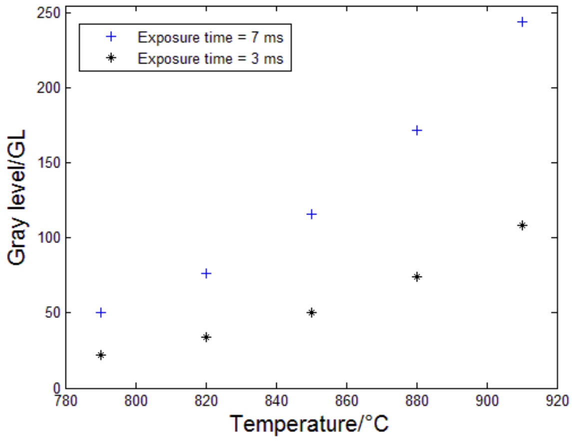

Fig. 2: Effect of temperature on gray level of image at the exposure time of 7 ms and 3 ms.

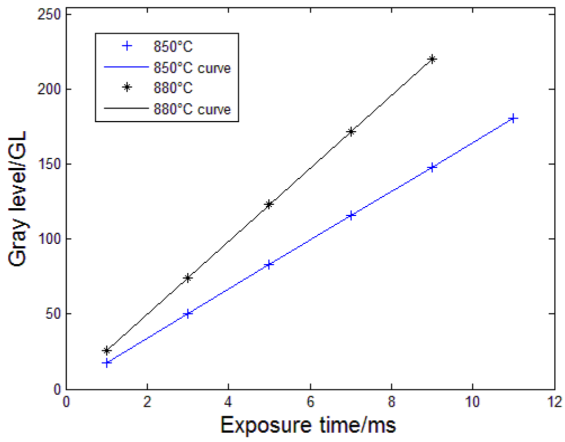

Fig. 3: Relationship between exposure time and gray level of image at the fixed temperature of 850℃ and 880℃.

2.2 Radiometric model

Based on the relationship between exposure time and gray level mentioned above, the intensity, which is defined as gray level normalized by exposure time, is introduced in radiometric model of camera. The radiometric model describing the relationship between intensity and temperature is given as follows [9]:

$$I_n(T) = \frac{I}{\tau}(T) = k_w \exp\left(\frac{-C_2}{\lambda_x(T)T}\right) \tag{1}$$

where I_n is the intensity, I is the gray level value of the region of interest registered by the silicon based camera, τ is the exposure time of camera, T is the absolute temperature, C_2 is the second Planck's constant (1.44×10^{-2} m.K), $\lambda_x(T)$ is the extended effective wavelength introduced into the radiometric model because the spectral density of energy in the near infrared spectral band will move to lower wavelengths when the temperature increases. The extended effective wavelength $\lambda_x(T)$ can be given as follows [11]:

$$\frac{1}{\lambda_x(T)} = a_0 + \frac{a_1}{T} + \frac{a_2}{T^2} + \frac{a_3}{T^3} + \cdots + \frac{a_n}{T^n}, (n = \infty) \tag{2}$$

where a_0, a_1, a_2, a_3, $\cdots$, a_n are parameters which should be determined by radiometric calibration process as well as the parameter k_w in Eq. (1). Due to the short range of temperature from 700 to 1000℃ chosen in our study, it is enough to calculate a radiometric model with three parameters which are the following: k_w, a_0, a_1 [10]. Fig. 4 shows the calculated radiometric model which is based on the data acquired by blackbody and the Table 1 gives the values of the parameters.

k_w (gl)	a_0 (m^{-1})	a_1 (m^{-1}.T)
2.12×10^{12}	2.0923×10^{6}	-6.1935×10^{8}

Table 1: Radiometric model parameters

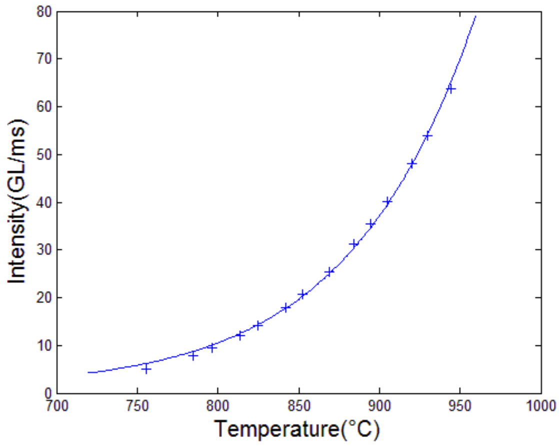

Fig. 4: Radiometric model.

2.3 Prediction of exposure time to control gray level

In this study, we propose an approach to precisely and continuously adjust automatically the exposure time to get a stable gray level of images whatever is the temperature evolution. The schematic diagram of principle is shown in Fig. 5. At the beginning first two images (as indicated by black points) are taken when the constant exposure time is maintain (i.e., τ (1) = τ (2) = τ). If the exposure time is maintained, the gray level of image will change to the positions of hollow points. The objective of this approach is to maintain the mean gray level of images constant. Thus the exposure time should be changed so that the mean gray level of images taken after the third one are equal to that of the first one (as indicated as red points).

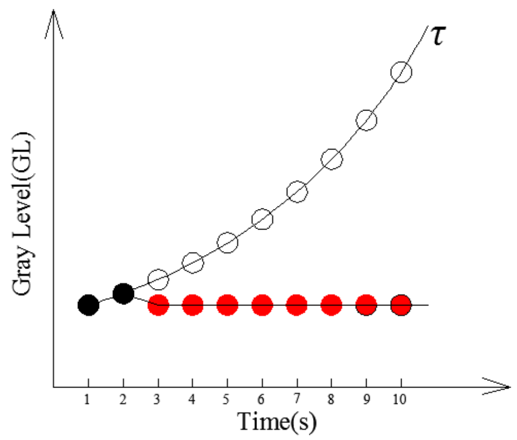

Fig. 5 Schematic diagram of principle of the approach.

From the radiometric model, it is apparent that the intensity, which is only related to temperature, is defined as the gray level of image normalized to exposure time. Based on the first two images, the intensity of the third one will be predicted by an algorithm. The flow chart to obtain the next exposure time is shown in Fig. 6, a critical value ε is introduced because it is impossible to acquire two identical images in reality. Then a criterion equation is given as follows:

$$\left|\overline{gl(i-1)} - \overline{gl(1)}\right| \le \varepsilon, i \ge 3 \quad (3)$$

If the difference in mean gray level between the image taken after the second one $\overline{gl(i-1)}, i \ge 3$ and the first one $\overline{gl(1)}$ is less than the critical value ε, the temperature of these two cases will be constant. Due to constant temperature, we can predict that the next exposure time $\tau(i)$ is equal to the last one $\tau(i\text{-}1)$. Otherwise, the temperature changes. Based on the intensity values of two images acquired before, we can use an algorithm to predict the next intensity. The radiometric model is derived from the Planck's law, and the basic equation is exponential function.

Thus, we propose a Planck's algorithm, given as follows:

$$I_n(i) = \frac{I_n(i-1)^2}{I_n(i-2)} \quad (4)$$

The Eq. (4) can be expanded:

$$I_n(i) = \frac{\overline{gl(i)}}{\tau(i)} = \frac{I_n(i-1)^2}{I_n(i-2)} = \left[\frac{\overline{gl(i-1)}}{\tau(i-1)}\right]^2 * \frac{\tau(i-2)}{\overline{gl(i-2)}} \quad (5)$$

In order to make sure that $\overline{gl(i)} = \overline{gl(1)}$, the next exposure time can be obtained by:

$$\tau(i) = \overline{gl(1)} * \left[\frac{\tau(i-1)}{\overline{gl(i-1)}}\right]^2 * \frac{\overline{gl(i-2)}}{\tau(i-2)} \quad (6)$$

Then, a software which can adjust the exposure time automatically is prepared based on the algorithms proposed above.

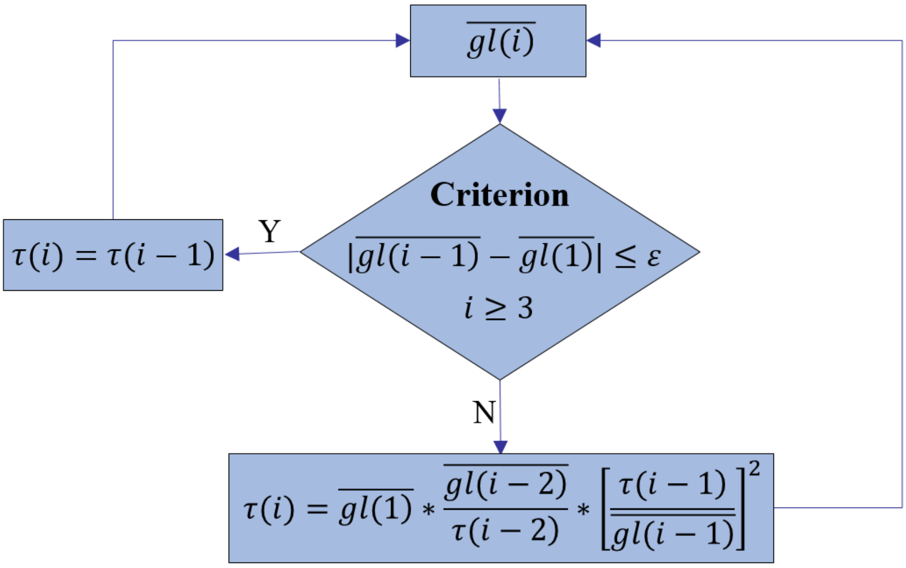

Fig. 6 Flow chart of the method to predict the exposure time to maintain the gray level of image constant.

3 Verification of the approach

The heating process of black body experiments were used to identify our approach to control the gray level of image. The CMOS camera is controlled by the software internally developed in Labview to in situ the heating process of black body experiments. It approximately takes 10 ms to calculate the prediction of the exposure time and the camera takes 70 ms to change the exposure time in its parameter. So the acquisition frequency of the camera will be at the maximum at 5 Hz for now. The temperature of black body experiments increases from 700 to 1000℃, as shown in Fig. 7.

When the critical value ε is set as 0.05 and the frequency of camera to take image is set as 1 HZ, we choose the images from No. 150 to No. 550 (as indicated by dotted line in Fig. 7) to plot the figure which describes the exposure time (Fig. 8), mean gray level (Fig. 9) and error (Fig. 10) with temperature evolution. The error which is defined as the difference between mean gray level of image and the mean gray level of first image normalized by the mean gray level of first image is given as follows :

$$error = \frac{\left|\overline{gl(i)} - \overline{gl(1)}\right|}{\overline{gl(1)}} \tag{7}$$

It can be found that exposure time, gray level and error are following the special function with the temperature evolution. All these things indicate that the approach to maintain gray level constant is feasible and reliable.

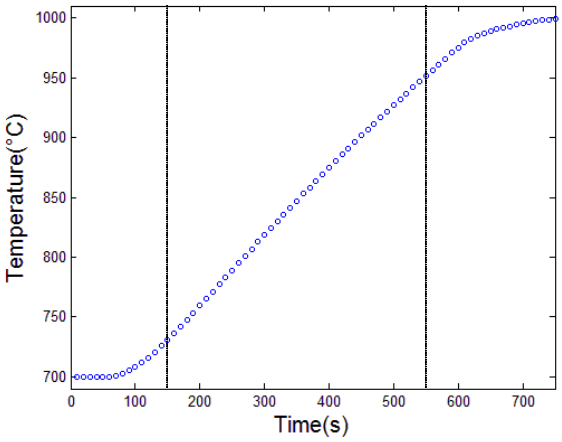

Fig. 7 Temperature of black body at different time.

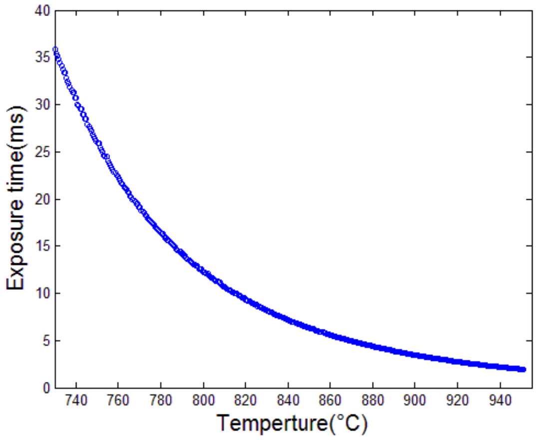

Fig. 8 Exposure time adjusted automatically at different time.

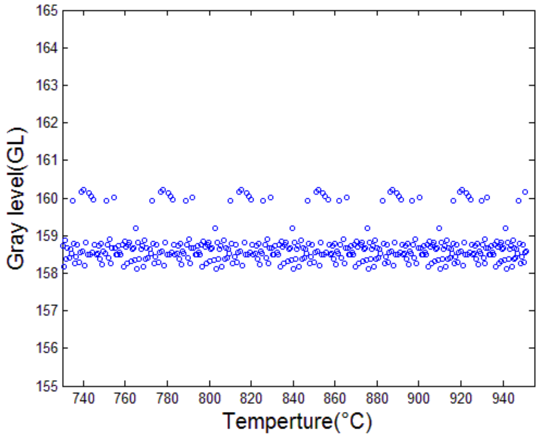

Fig. 9 The mean gray level of image at different time.

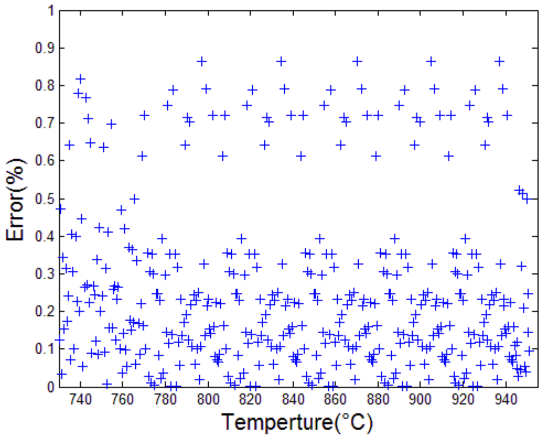

Fig. 10 The error at different time.

4 Conclusions and future developments

In this study, an approach based on Planck's law for precisely and continuously adjusting automatically the exposure time to get a stable gray level of images whatever the temperature evolution is proposed to deal with the variation of gray level with temperature evolution when the silicon-based camera is intended to be used to measure the thermal field. Black body experiments were also conducted to verify this approach. Experimental results indicate that the method is feasible and reliable.

The results presented in this study are only the first step of a more ambitious work. The next work is to conduct experiment with different surface emissivity. Then the thermal field of a sample surface which has different emissivity will be obtained by near infrared thermography.

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