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Effect and correction of the shift in spectral images for polychromatic thermography

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ABSTRACT

This articles investigates the temperature errors due to chromatic aberration in multiwavelength thermography methods. The Chromatic aberration leads to a shift in the perspective projection of a point in the 3*D* space on the image formed at different wavelengths. This shift causes an error in the temperature field calculated by polychromatic methods, from the fusion for each pixel of radiance temperature images at different wavelengths. The temperature error can reach 40% on a sample with high spatial non-uniformities, due to wide variations of emissivity. This paper suggests an approach to correcting the chromatic aberration that is based not on equipment but on software, coupled with a calibration, using Digital Image Correlation (DIC). This experimental technique is a 2D optical method used in mechanical engineering, for inferring a deformation of a plane structure's surface from a displacement field calculated by correlation between pixels of two successive images. This paper applies the technique to achieve the field displacement induced between two images at two wavelengths by chromatic aberration. After applying this correcting displacement field, the temperature error decreases from 40% to 1% for the pixels located at the boundary of two areas with different emissivities.

1. Introduction

Thermography is a widely-used technique today in numerous applications, such as defect detection ([3]), thermal properties characterization ([8]), temperature measurement ([13,21]) or military surveillance [25]. In applications that require quantitative measurements of temperature fields, the influence of the emissivity, which is a thermo-optical property of the material, needs to be investigated. To bypass the need for an absolute knowledge of the emissivity, some techniques formulate assumptions and models of its spectral behaviour and solve, at different wavelengths, a system of equations using this modelling with images of radiance temperature. The number of equations depends on the parameters used in the emissivity modelling, and the choice of wavelengths can be critical [18]. Solving this system of equations from images of radiance temperature at different wavelengths is performed for each pixel to retrieve the true temperature and emissivity fields. For example, monochromatic thermography considers the emissivity as a known value. Bichromatic thermography [19] assumes that the emissivity ratio at two wavelengths is known. Polychromatic thermography [6] is based on different emissivity modelling versus wavelength (polynomial, exponential, etc.). Active bichromatic thermography [2] adds equations to take into account strong parasite reflections on a specular metallic surface. Bichromatic thermoreflectometry [7] evaluates the emissivity ratio at two wavelengths by a reflectometry measurement.

The implementation of these techniques relies on systems of spectral selection of the thermal radiation. Especially for bichromatic techniques, the use of dual-band cameras [1,17], is an attractive solution. These cameras usually operate both in the 8–12 μm Long Wavelength Infrared (LWIR) and the 3–5 μm Medium Wavelength Infrared (MWIR) spectral bands. Both operating spectral bands may be too far to be able to make any assumptions about the emissivity. Moreover, a spectral selection must often be added to reduce the bandwidth of each spectral band by using interference filters. Whether with dual or single band cameras, spectral selection is very often performed by the switching of interference filters. Unfortunately, interference filters on the lens introduce optical defects [10] like ghost and narcissus effects and chromatic aberration. These defects are widely presented in the literature [15].

Indeed, the optical index of the material of lenses and filters

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depends on the wavelength, and the optical paths for different wavelengths differ significantly. The perspective projection of a 3D point of the object on the focal plane of the detector array is then shifted from one wavelength to the other. The images are thus distorted in two components: lateral (shift in the images) and longitudinal (de-focussing). This paper only addresses the lateral distortion of the images at several wavelengths.

For polychromatic thermography techniques, based on the resolution of a system of equations with images at different wavelengths, their shift means that for a given pixel, the matching 3D point in the scene is not the same for different wavelengths. The resolution for each pixel is thus physically inconsistent, which induces an error in the temperature field calculated. A correction method needs to be implemented to ensure that the same 3D point is projected onto the same pixel regardless of the selected wavelength. The ideal method would be to include it in a prior calibration procedure that can be adapted to any system consisting of cameras, lenses and filters.

Many articles address the problem of the correction of chromatic aberration, but they deal mostly with the visible spectrum for colour cameras (where the RGB channels are shifted), and they often concern photogrammetry applications [14]. Chromatic aberration can initially be reduced by taking a few precautions, such as closing the aperture of the lens to a maximum so that only the centre of the lens is used. However, this is very restrictive for low flux applications. Alternatively, specific equipment can be added to limit the effect of chromatic aberration. Telecentric lenses [20] allow the rays to be turned perpendicularly to the detector plane array. The drawbacks to this method are that it gives a small depth of field and a significant length (around 50 cm). Achromatic and apochromatic lenses [23], with a suitable surface treatment on the glass, enable the correction of optical paths for two or three wavelengths. In addition to their rather high prices, these components must be added to a lens with a compatible focal length, which restricts their use to fixed focal lenses and lowers the signal received by the detectors.

Another solution, easily adaptable to any system and which also removes the remaining defects of the previous solutions, is to correct the distortion directly on the images by image processing procedures. The first class of procedures benefits from the features of the scene under view. In Ref. [4], automatic detection of edges and contours is set up in the image, and image warping is applied. The second class of procedures includes the modelling of chromatic aberration in which parameters are estimated in a calibration step using a specific pattern [11,15]. These methods are dedicated to colour cameras which use a colour filter array consisting of a mosaic of spectral filters in front of the image sensor. The most common spectral filter array is the Bayer filter which alternates red and green filters for the odd pixel rows and green and blue filters for the even pixel rows of the image sensor. The image processing procedure [12] precisely determines the geometric distortions of the red and blue image pixels in comparison to the green reference pixel. For polychromatic thermography systems, spectral filters are not dedicated to individual pixels but to all the pixels. The chromatic aberration is not between pixels but between images acquired at different wavelengths.

The suggested procedure for image processing does not compute displacement between pixels for transferring the perspective projection of 3D points from the green pixel to the red or blue ones, but rather it computes a displacement field on the whole image so as to transfer the perspective projection of 3D points to the same pixel of two images acquired at two different wavelengths.

The displacement fields are calculated by the Digital Image Correlation (DIC) method, which is able to provide dense displacement fields. This method is usually used in mechanical engineering [24] to measure displacement fields between two images and thus derive strain fields. It is therefore assumed that the difference between the images comes only from the effect of the displacement field of the observed structure. In our case, this technique measures the displacement field of a surface of an image at a given wavelength with respect to a reference image at another wavelength. It is therefore assumed that any difference between the reference image and the distorted image comes only from the effect of the chromatic aberration between the two wavelengths.

The first part of this paper seeks to evaluate the temperature error due to chromatic aberration in a bichromatic thermography system. This study is performed on a specific sample, called the “two-emissivity sample”, showing two areas with two very different emissivities. The paper then presents the suggested image processing procedure based on the DIC method, which is applied to calculate the displacement field between two images at two wavelengths acquired on a system composed of a lens and interference filters. The displacement field is determined within a simple calibration step and applied in-line to correct the distortion due to the chromatic aberration. Finally, the method is validated on the previous two-emissivity sample, showing a significant decrease in the temperature error at the boundary of the two areas.

The paper is organized as follows. Section 2 is dedicated to the evaluation of the effects of the bichromatic thermography system. Section 3 provides the measurement of the image shift at different wavelengths by DIC methods implemented in the commercial software, Vic2D. Section 4 presents the correction protocol and shows the gains in terms of accuracy in temperature measurement.

2. Temperature error of bichromatic thermography due to chromatic aberration

2.1. Principle of bichromatic thermography

Bichromatic thermography is a non-contact temperature measurement method which does not require the absolute knowledge of emissivity; only the ratio at two wavelengths is necessary. The standard system is composed of a camera equipped with two interference filters at wavelengths λ_1 and λ_2. Two radiance temperature fields $T_{R1}(u,v)$ and $T_{R2}(u,v)$ can easily be calculated for each pixel of coordinates (u,v) from two images acquired at the two wavelengths using a previous radiometric calibration performed on a blackbody for both filters (see article [22]). Knowing the radiance temperature fields and the emissivity ratio field $\varepsilon_r(u,v)$ of the scene under view, the colour temperature field $T_C(u,v)$ is calculated according to Eq. (1).

$$\begin{aligned}
\frac{1}{T_C(u,v)} &= \frac{1}{T_r(u,v)} + \frac{\Lambda}{C_2}\ln\varepsilon_r(u,v) \\
\frac{1}{T_r(u,v)} &= \Lambda\left(\frac{1}{\lambda_1 T_{R1}(u,v)} - \frac{1}{\lambda_2 T_{R2}(u,v)}\right) \\
\varepsilon_r(u,v) &= \frac{\varepsilon_1(u,v)}{\varepsilon_2(u,v)}, \quad \Lambda = \frac{\lambda_1\lambda_2}{\lambda_2-\lambda_1}
\end{aligned} \tag{1}$$

The formulation of the Eq. (1) is based on Wien's approximation (available when $\lambda T \leq 3000$ µm K and suitable for $\lambda \in [0.9–1.7$ µm$]$ spectral and $T \in [300–1000$ °C$]$ thermal range) and with assumptions of no reflected radiation on the sample and no atmospheric attenuation.

Obviously, this equation shows that the colour temperature field comes from the fusion, at each pixel, of four physical quantities: the radiance temperature fields and the emissivity fields at two wavelengths. These four quantities must be spatially coherent. A