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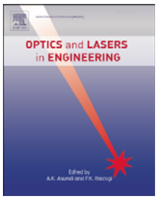

Compensating lateral chromatic aberration of a colour fringe projection system for shape metrology

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ABSTRACT

In this paper we demonstrate a technique to compensate for lateral chromatic aberration between the red, green and blue channels of a colour fringe projection system. For measurement of colourful artefacts it is important to be able to combine data from the different colour channels to accurately quantify the artefact's form, with colour capture also providing colour texture information that can be mapped onto the form data. However, the use of conventional refractive lenses in the projection and imaging systems introduce dispersion and hence lateral chromatic aberration that modifies the measured phase differently in each of the colour channels. A linear compensation model is proposed using phase maps from the different colour channels to enable the magnitude of lateral chromatic aberration to be calibrated. The required performance of the technique is established via simulations and the use of the technique over a typical depth of field has been confirmed experimentally. Results from a white reference plane, a telephone and a colourful painting show that the proposed method compensates lateral chromatic aberration from the captured shape data. The probability of calculating the correct fringe order by unwrapping the phase between the different colour channels is typically 99.9%.

1. Introduction

Non-contact optical full-field 3D sensing is an active research field in machine vision that serves applications across the digital economy [1,2]. Three major challenges in full-field 3D sensing have been the measurement of objects with discontinuities or large slopes, achieving fast data acquisition and combining the resulting shape measurements with colour texture data. Temporal phase-unwrapping [3–6] or a combination of phase measurement and gray-code projection [7] have been explored to resolve the mod 2π difficulty in using fringe projection to measure artefacts containing discontinuities or large slopes. However, temporal phase analysis requires an increased number of fringe patterns hence data acquisition times are increased. Conversely, real time 3D data capture has been achieved using phase stepping and a single pitch of projected fringes [8], but relies on spatial unwrapping to identify fringe order and hence this method cannot resolve discontinuities. An optimum multi-frequency selection method was introduced to determine the absolute fringe order at each pixel independently where a geometric series of synthetic wavelengths are defined to maximize the overall process reliability by using a minimum number of projected fringe patterns [9,10]. For commercial data projectors the resolution of the projector can be reached using only three different fringe pitches whilst giving a probability of 99.73% (i.e. 6σ) of calculating the correct absolute fringe order [11].

In many applications surface colour information is required as well as shape, for example in artefact cataloguing or facial reconstruction surgery. In these cases it is necessary to combine the measurement of shape and colour [11–13]. The use of separate detectors for the two measurands leads to the risk of information mismatch, hence it is preferable and reduces overall system cost to use a single colour detector. For highly coloured artefacts some surface regions may only give sufficient scattered light for accurate shape calculation in different (single) colour channels for different pixels and hence for generic objects there is the need to combine form data from all the colour channels [12]. However, any distortion of the fringes between colour channels will cause errors in the reconstructed shape data. For artefacts where sufficient light is scattered in all colour channels from all points on the surface there is the opportunity to reduce the data capture time by encoding the multiple fringe pitches into the different colour channels for parallel acquisition. It is particularly efficient to use the optimum 3-frequency projection approach for fringe order calculation where the different fringe frequencies are

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encoded into the primary colour channels. In such arrangements there is a similar requirement to combine phase information from all colour channels to enable fringe order calculation at each pixel and the system is sensitive to the exact numbers of fringes projected across the field of view [9–11].

In any refractive optical system with multiple information channels based on chromatic separation the presence of dispersion leads to chromatic aberration. Chromatic aberration can be categorized into lateral chromatic aberration and longitudinal chromatic aberration. Longitudinal chromatic aberration affects the sharpness of the fringes (different colour fringes are focussed at different distances) and in practise is found to give an acceptable reduction in the modulation depth of the fringes. However, lateral chromatic aberration has a large effect on fringe order calculation since it changes the overall magnification of the fringe patterns, giving a zoomed in or out variation between the colour channels. Therefore, the numbers of projected fringes used in the optimum 3-frequency selection method to determine the fringe order number should be different from the number of fringes used to form the image projected by the projector. Even where data from a single colour channel is used at a pixel for unwrapped phase calculation, the presence of lateral chromatic aberration generates artificial steps in the shape data when combining information from the other colour channels at other pixels. For the colour fringe projection system, chromatic aberration comes from the lenses of the Digital Light Processing (DLP) video projector and the 3-chip colour CCD camera. Using high-quality lenses for the camera and projector can reduce but not eliminate the measured phase errors from lateral chromatic aberration. Previously, the compensation of chromatic aberration has been explored in digital holography where the longitudinal and lateral position of features in the reconstructed image scale with the wavelength used to form the reconstruction [14–17]. Ferraro et al. explored chromatic aberration compensation techniques based on reconstructing the digital holographic image at different depths as the wavelength is varied [15–16]. Mann et al. applied a flat, blank portion of the measured object to record a flat-field reference hologram, so that residual optical aberrations in the reconstructed image can be corrected for [17]. Millán et al. developed a dynamic compensation method for chromatic aberrations by using a tunable spectral filter in conjunction with a phase diffractive lens [18]. In these cases [14–18], the magnitude of the chromatic aberration is relatively high as the scale of the image formed depends directly on the wavelength used for illumination.

In this paper, a novel linear compensation method will be explored to compensate lateral chromatic aberration resulting from the refractive projection and imaging lenses in a colour fringe projection system. The following section introduces the principle of the proposed method. In Section 3, simulated and experimental data are used to test the approach. Section 4 gives some comments regarding further opportunities and Section 5 concludes the paper.

2. Principle

In a colour fringe projection system when phase maps are determined on two colour channels from projected patterns of straight and parallel fringes with the same pitch the calculated phases along a row of pixels are different due to lateral chromatic aberration. From experimental data, the difference of the two phase maps along a row, which is orthogonal to the fringes, was found to have a linear relationship with respect to pixel position as shown in Fig. 1. The blue channel was chosen as the baseline with respect to the red and green channels. The top and bottom rows are the difference of the red and green channels with regard to the blue channel along the row direction. The first, second and third columns correspond to the top, middle and bottom rows of the captured images, respectively. The phase differences in Fig. 1 between the red and blue channels are larger than those between green and blue due to the imperfect compensation for aberrations in the lenses and the additional separation between red and blue wavelengths. Based on the approximately linear dependence of the phase error with position across the image, lateral chromatic aberration can be calibrated beforehand for a given colour fringe projection system. In the following, the red channel was chosen to show the details of how the lateral chromatic aberration can be calibrated with respect to the blue channel.

When red and blue fringe patterns containing the same number of fringes (i.e. having the same pitch) are projected onto a flat reference plate, the captured colour fringe patterns contain F_r and F_b fringes. The difference in the number of fringes obtained across the field of view of the camera we denote by $\varepsilon_r = F_r - F_b$, and refer to as *fringe aberration*, coming from lateral chromatic aberration. In general, fringe aberration ε_r is a function of number of projected fringes, working distance, pixel position along the row direction, and the colour channel used. Since the phase difference along the row direction has an approximately linear relationship to pixel position, the fringe aberration between two colour channels for a given number of fringes across the field can be determined by subtracting the two phases along that direction.

Assuming that the projected number of fringes from the projector is F, the captured number of fringes is smaller than F in order to ensure that the patterns cover the whole field of view. By using the optimum 3-frequency selection method, two fringe pattern sets (each composed of four phase steps at three patterns of different pitches for a total of 12 fringe patterns per colour channel) are projected and captured from the red and blue channels, respectively, and the absolute (unwrapped) phase maps $\phi_r(m,n)$ and $\phi_b(m,n)$ calculated [9–11], where $m = 1,2,\ldots,M$, $n = 1,2,\ldots,N$ are the indices of pixels in the row and column directions and M and N are the number of pixels in the captured image, respectively. The phase difference between the two channels is

$$\Delta\phi_{rb}(m,n) = \phi_r(m,n) - \phi_b(m,n). \tag{1}$$

Since the phase difference has a linear relationship to pixel position along each row, the fractional error, FE_{rb}, produced from lateral chromatic aberration can be calculated from

$$FE_{rb}(m) = (\Delta\phi_{rb}(m,N) - \Delta\phi_{rb}(m,1))/(\phi_b(m,N) - \phi_b(m,1)). \tag{2}$$

The fractional error is normalised by the unwrapped phase across the image in the reference channel hence it should have a constant value irrespective of the number of projected fringes. A more useful measure in practise is the fringe aberration, $\varepsilon_r(m)$, as this value maybe used directly to correct for lateral chromatic aberration and is defined for a specific number of projected fringes F as

$$\varepsilon_r(m) = F \times FE_{rb}(m). \tag{3}$$

Hence, when calculating the absolute fringe order [10], the values for the number of fringes projected across the field of view are corrected as $F - \varepsilon_r(m)$, instead of the number of fringes, F, used to create the image projected by the DLP projector.

The fringe aberration for a certain number of projected fringes between green and blue channels can be determined in the same way.