Optics Communications 282 (2009) 4595–4601

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Off-axis low coherence interferometry contouring

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ARTICLE INFO

Article history:
Received 20 May 2009
Received in revised form 18 August 2009
Accepted 21 August 2009

PACS:
42.25.Hz
42.25.Kb
07.60.Ly

Keywords:
Interferometry
Low coherence
Contouring
Off-axis

ABSTRACT

In this article we present a method to achieve tri-dimensional contouring of macroscopic objects. A modified reference wave speckle interferometer is used in conjunction with a source of reduced coherence. The depth signal is given by the envelope of the interference signal, directly determined by the coherence length of the source. Fringes are detected in the interferogram obtained by a single shot and are detected by means of adequate filtering. With the approach based on off-axis configuration, a contour line can be extracted from a single acquisition, thus allowing to use the system in harsh environment.

1. Introduction

There is a large panel of techniques available for optical 3D measurements of rough or diffusing macroscopic objects with a sub-millimeter accuracy [1]. Incoherent light can be used with fringes projection techniques, where the fringes deformation is considered in order to retrieve the depth information. Moiré pattern techniques also exist, in which two gratings are used to generate contour fringes [2]. Photogrammetry employing mainly stereo vision procedures to obtain tri-dimensional shape are also available [3].

Interferometric measurements are widely used to obtain contouring of macroscopic objects, in particular the so-called electronic speckle pattern interferometry technique (ESPI). Jaisingh and Chiang obtained the surface of a regular light bulb [4], using a setup with double exposure. Joenathan et al. used a setup containing a Fourier-filtering part to extract the information from a specklegram [5]. Rodriguez-Vera et al. have used a fibered setup for out-of-plane sensitive ESPI [6]. Prieto and Garcia-Sucerquia reported contouring of macroscopic objects with a phase-difference method [7]. All these techniques require at least a double exposure procedure. Balboa et al. reported 3D measurements using superluminescent diode and multimodes laser diodes in an optical fiber based interferometer [8], using a five step algorithm for fringe amplitude extraction. One way to access tri-dimensional measurement is to achieve phase change by using at least two wavelengths, as Tatam et al. reported [9], or a source emitting an extended spectrum. This gives rise to the Fourier-transform speckle profilometry [10]. Another possible method for phase extraction from a specklegram is to use spatial phase shifting (SPS), in which the phase of a pixel is estimated from the intensity of the surrounding pixels, instead of the values of the same pixel at different times, as it is the case for time phase shifting. Bhaduri et al. achieved SPS with the use of a double aperture mask [11]. In order to overcome the limitation of multiple acquisitions, many efforts were done to build interferometers allowing to record multiple interferograms at the same time. Recently, Hrebesh et al. proposed a system for the acquisition of three phase-stepped interferograms and a reference image at the same time, allowing single-shot low-coherence time-domain profilometry [12].

When using a broadband light source in a typical out-of-plane sensitive ESPI interferometer, the process of extracting the location of the coherent superposition of two waves is referenced in the literature as the "coherence radar" technique. Dresel et al. used a simple Michelson configuration, with a piezo-electric actuator to take three phase-stepped acquisitions in order to extract a contour depth [13]. It is also possible to use short light pulses, in this case the method is called "light-in-flight holography" [14]. Carlsson

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0030-4018/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2009.08.048

et al. further modified the technique using a blazed grating to introduce a spatially varying delay across the reference beam profile [15,16].

In this paper a novel arrangement for low coherence interferometry is presented. Similarly to the coherence radar technique, the goal is to achieve contouring by isolating the zone in the acquired image where fringes are created. It will be shown that, with a well designed off-axis configuration, it is possible to achieve contour extraction in only one acquisition, removing the need for phase-shifting or multiple acquisitions with different wavelengths. First, the setup and the procedure used for fringes extraction are carefully described. The optical system has been totally simulated, and results of the simulation are compared with measurements. They show fair agreement. Finally, different results are presented. Namely, the first on a tilted plane used for technique validation and precision evaluation, the second one on the inner side of a cylinder, and the last on a wooden pencil tip.

2. Material and method

2.1. Setup

We achieve curve level extraction with the use of the modified smooth reference wave speckle interferometer depicted in Fig. 1. The source is a reduced coherence length laser diode (LD), with a coherence length of about 0.3 mm. A beam splitter (BS1) separates the collimated beam generated by the LD into the reference beam (R) and the object beam (O). The reference beam is directed to a delay stage (DS), composed of two mirrors (M1 and M2), mounted on a motorized axis. A lens (L1) is placed in the object arm of the interferometer. It is used to widen the illuminated area of the object and to form an image at the CCD plane. The adjustable diaphragm (D) is an essential part of the setup: it is used to limit the aperture of the system, thus making possible to create interferences composed of fringes modulated by a slow varying speckle pattern. L2 is used to adapt the spherical reference wave in order to match the illumination geometry.

The intensity of two waves with finite temporal coherence can be expressed as [17]:

$$I = 2I_0[1 + |g(\tau)| \cos\phi(\tau)], \tag{1}$$

where $g(\tau)$ is the complex degree of temporal coherence, with τ the delay time between the two waves. ϕ is the phase difference induced by τ. Eq. (1) expresses the ability of a wave to interfere with a time delayed version of itself. For a light source with a bandwidth of $\Delta\nu$, the visibility of the fringes for two waves delayed by $\tau_c \approx 1/\Delta\nu$ is 0.5. The path that light has traveled during τ_c is called the coherence length (L_c). Therefore, interference terms will be present only on points in the image for which the optical path difference (OPD) between R and O is below L_c. Extracting from the image the positions where these interference fringes are situated gives a depth signal for macroscopic objects (with height much greater than L_c), and an easy contouring procedure by either shifting R or O. On the setup depicted on Fig. 1, the DS is used first to adjust the length of the reference arm in order to match the length of the object arm, then the object is scanned to retrieve different curve levels.

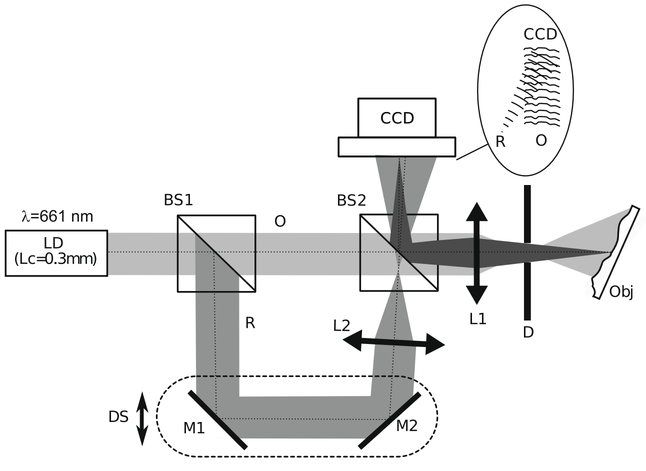

Fig. 1. Experimental interferometric setup used. LD: laser-diode with low coherence length. BS1, BS2: beam splitters. L1, L2: Lenses. D: adjustable diaphragm. Obj: scattering sample. DS: delay stage. CCD: charge-coupled device camera.

M2 is placed so that there is a small angular mismatch at BS2 between the optical axis of R and O, which in turn can be regarded as interferences of spherical waves coming from off-axis points. This creates "carrier fringes" on the interferogram. In the Fourier spectrum, this separates the interference terms and the zero-order term. Detecting the presence of these fringes with a local Fourier spectrum evaluation becomes then possible and provides a simple and efficient way of extracting the area on the image where coherent superposition of the two waves occurs, thus making possible of extracting a curve level in only one acquisition.

2.2. Contour lines extraction

As pointed out in the previous subsection, it is possible to create fringes that are discernible with a small angular mismatch between the optical axis of R and O. Extracting the area where there are fringes could also be achieved by phase shifting manipulation. However, this would involve the acquisition of at least two interferograms, thus increasing the overall acquisition time and the sensitivity to perturbations.

Common procedure to extract fringes in an interferogram is to simply process its Fourier transform with adequate bandpass filter. However in our case this approach fails, mainly due to the fact that the fringes to extract may be very low contrasted and are highly localized, so that after numerical calculation of the Fourier transform, the magnitude of the spatial frequencies in the bandpass filter are approaching the noise limit.

The interferogram is here processed with a window filter, defined by evaluating the Fast Fourier Transform (FFT) in a neighborhood.

The output value of the pixel that is processed is the maximal amplitude of the local spectrum, after zero-order removal:

$$\begin{aligned} y(p,q) &= \max_{m,n\in[1,M-1]} |h_{m,n}|, \quad \text{where}: \\ h_{m,n} &= \sum_{k=0}^{M-1}\sum_{l=0}^{M-1} x(p+k,q+l) \times e^{-i(mw_0(p+k)+nw_0(q+l))}, \\ &\text{with}: \; p,q \in [0,N-1]. \end{aligned} \tag{2}$$

Eq. (2) corresponds to a local measurement of the high frequencies contribution, with $x(p,q)$ the input interferogram, w_0 the slowest pulsation considered, $h_{m,n}$ the window filter and $y(p,q)$ the filter output value. It is also possible to evaluate the mean value or the cumulative sum of a certain bandwidth of spatial frequencies. It was observed that the output of the maximum value is sufficiently selective, providing that there is no sinusoidal variation of the intensity induced by the object itself that falls into the frequency calculated by the FFT.

Fig. 2a shows the obtained signal for the extraction of a meridian on a metallic cylinder. Fig. 2b and c shows the different components of the FFT (after zero-order removal) calculated over a neighborhood of 8×8 pixels, when the pixel of interest belongs to an area where OPD is smaller than L_c and greater than