Optics Communications 366 (2016) 94–98

Contents lists available at ScienceDirect

Optics Communications

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

Invited Paper

# Rolling Shutter Effect aberration compensation in Digital Holographic Microscopy

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ARTICLE INFO

*Article history:*
Received 27 October 2014
Received in revised form
11 December 2015
Accepted 18 December 2015
Available online 28 December 2015

*Keywords:*
CMOS
Digital Holographic Microscopy
Rolling Shutter Effect
Optical phase aberration

ABSTRACT

Due to the sequential-readout nature of most CMOS sensors, each row of the sensor array is exposed at a different time, resulting in the so-called rolling shutter effect that induces geometric distortion to the image if the video camera or the object moves during image acquisition. Particularly in digital holograms recording, while the sensor captures progressively each row of the hologram, interferometric fringes can oscillate due to external vibrations and/or noises even when the object under study remains motionless. The sensor records each hologram row in different instants of these disturbances. As a final effect, phase information is corrupted, distorting the reconstructed holograms quality. We present a fast and simple method for compensating this effect based on image processing tools. The method is exemplified by holograms of microscopic biological static objects. Results encourage incorporating CMOS sensors over CCD in Digital Holographic Microscopy due to a better resolution and less expensive benefits.



## 1. Introduction

A CCD/CMOS used to record holograms must resolve the interference pattern resulting from superposition of the reference wave with the waves scattered from different object points. In the last decades, in order to achieve digital holograms, CCD sensors have been chosen as the favorite ones for replacing the classical holographic films [1]. This is due to its ability to meet the minimum resolution requirements despite of its high cost. CMOS sensors have many advantages in comparison to the CCD sensors; they offer higher resolution, less thermal noise and guarantee higher frame rates at a significantly reduced cost compared to the CCD ones. Moreover, the main difference between CMOS and CCD sensors lies in the signal readout mechanism. To obtain signals corresponding to an image frame all photodiodes of CCD are exposed to a scene simultaneously; whereas, in most CMOS sensors each image row, being sequentially accessed, is given a different exposure time window, with a time delay defined by the sensor technology. Even though this readout mechanism has the advantage of minimizing buffer memory, it produces the so-called Rolling Shutter Effect (RSE) that distorts images of moving objects [2–4]. In this regard, it may represent a major obstacle in interferometry techniques. Although the aim of this paper is not an exhaustive study of how one type of device differs from another, we will focus on some properties that are sensitive to a particular application such as the Digital Holographic Microscopy (DHM) [1,5–9]. In the literature, several works report solutions for eliminating or mitigating RSE by using either mechanical or electrical devices or by mathematical algorithms that generally require multiple images of the same scene for synchronization [2,10]. These correction mechanisms are typically used in automatic vision devices or popular used cameras. Nevertheless, to our knowledge, methods for eliminating this effect for the case of images of digital holograms have not been developed yet.

During hologram recording, interference fringes are strongly sensitive to external noises, vibrations, etc.; causing spurious perturbations during the readout process which result in unwanted phase aberrations. These perturbations may vary in an unpredictable way from one acquisition to another because they depend on random external conditions, which are difficult to control. Since in many DHM applications accurate phase values must be extracted from the quantitative phase map [11], this aberration must be compensated in order to have access to reliable local information of the integrated optical path length (OPL) which can be used to measure either the integral refractive index or the topography of the object under study.

To overcome this drawback when using a CMOS as a recording device in DHM, a simple and fast methodology is proposed. It consists of a sequential application of image processing tools to

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http://dx.doi.org/10.1016/j.optcom.2015.12.048
0030-4018/

the continuous phase maps obtained from holograms of biological static objects. Experiments in holograms of uniform refractive index objects in non-vibration isolated environment have been conducted to quantify phase errors introduced by RSE. The numerical results of these experiments show that spurious phase variations introduced by RSE affect the true values of phase above the typical expected errors.

## 2. Overview of Digital Holographic Microscopy

The transmission DHM and phase image reconstruction techniques used for the present study have been described in Refs. 5, 6, and 7. Briefly, they consist of recording a hologram by means of interferometric set-up, onto a solid-state array detector such as a CCD or CMOS sensor and, subsequently, numerically reconstructing the information by means of a computer. A layout of digital holographic microscope prototype constructed for this purpose, is depicted in Fig. 1(a). Essentially, it is a Mach–Zehnder interferometer, whose object arm is fitted with a small microscope built by inserting an *X*–*Y* microscope stage to locate the sample and a microscope objective (MO) which acts as a magnifying lens and forms a real image of the object of interest. A TV camera, with a CMOS Bayer Array 2592 × 1944 pix$^2$, 1.75 µm square pixels, 8 bit deep and a frame rate up to 25 Hz is used to record digital holograms.

The reconstruction of the original microscopic field of view of the sample is performed digitally on a computer. This procedure simulates the reconstruction process in conventional holography, which consists of illuminating the hologram with a replica of the reference beam used in the registration stage. In this application, the reconstruction of holograms is carried out by using the angular spectrum propagation method [12]. As a result, an amplitude contrast image and a quantitative phase image are obtained. Illustratively in Fig. 2(a) hologram of a *Ceratium hirundinella* cell and the corresponding amplitude and phase images are shown.

## 3. Rolling Shutter Effect phase aberrations

To illustrate the unwanted phase aberration introduced by RSE we will focus our attention on Fig. 2(c). It is a two-dimensional phase distribution called the unwrapped phase image. As it can be seen, the image background is not uniform as it should be according to the homogeneity of the surrounding medium, in this case water. Thus, RSE shows up revealing itself as spurious horizontal ripples.

Usually, in DHM phase errors are quantified by computing the standard deviation (STD) noise level in a flat area of the unwrapped phase map [9,13]. In our case, this corresponds to the background of the image of Fig. 2(c). However, as it was emphasized, any background area is corrupted by horizontal ripples. To illustrate the influence of phase noise introduced by the RSE, phase values of profiles in the *X* (test rows in Fig. 2(c)) and *Y* (test column in Fig. 2(c)) directions corresponding to the background region in the unwrapped phase image are shown in Fig. 3.

In Fig. 3(a) both background *X* profiles (test row 1 and test row 2) have similar STD but have their phase mean average values differing in about 2 rad, which makes quantitatively evident RSE. In addition, by observing these graphs, it is noticed that phase values of the background deviate from a constant and that the deviation is much more significant in the vertical direction (Fig. 3(b)) than in the horizontal one, as evidenced from the scale of the graphics. According to this fact, in this paper we assume that the STD of the *X*-profiles gives a measure of experimental phase noise level not related with RSE. In a similar way, the STD of the Y profiles is a measure of the phase aberration introduced by the RSE.

The STD of various profiles analyzed, yield an average value of 0.16 in the *X* direction, and 0.54 in the *Y* direction. In terms of optical path length, these values represent an average phase error of approximately 16 nm and 54 nm respectively.

Horizontal nature of the background image ripples in Fig. 2(c), identified as phase aberrations introduced by the RSE, suggests that proper spatial filtering in the unwrapped phase spectrum could eliminate it. This procedure has some drawbacks when trying to automate the process, due to the randomness of the phenomenon. An alternative to avoid frequency filtering consists in removing the information of the aberration directly from the phase maps. This is accomplished by identifying and removing spurious phase values with image processing tools as explained bellow.

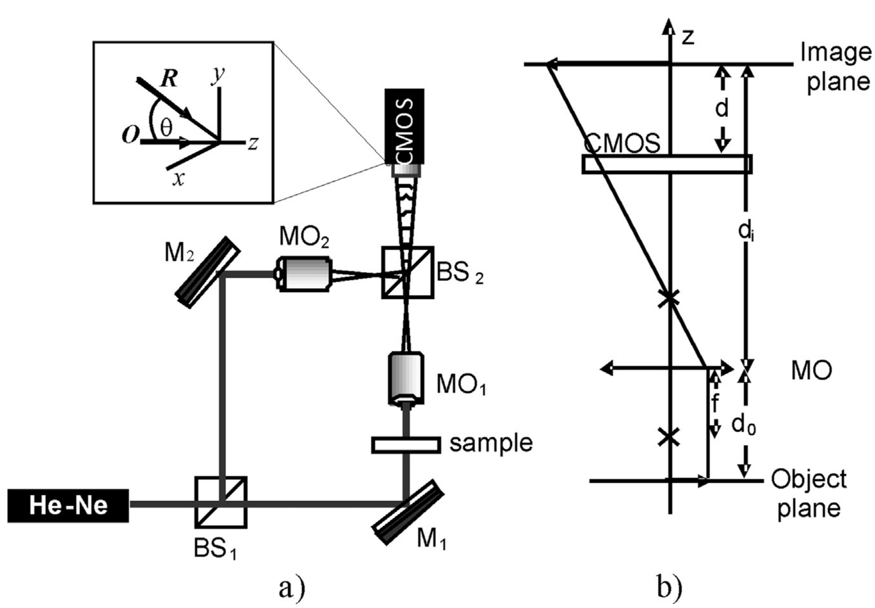


**Fig. 1.** : a) Experimental configuration; BS, beam splitters; M, mirrors; MO, microscope objectives. Inset: R, reference beam; O, object beam. b) Details of the microscope configuration in the object arm: $d_0$, object distance; $d_i$, image distance; *f*, MO focal length; *d*, distance of the image relative to the CMOS sensor.