Optics Communications 390 (2017) 57–60

Contents lists available at ScienceDirect

Optics Communications

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

Three-dimensional surface measurement based on the projected defocused pattern technique using imaging fiber optics

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A R T I C L E I N F O

Keywords:
Fiber optics imaging
Fringe analysis
Imaging system
Surface measurement
Three-dimensional sensing
Endoscopic imaging

A B S T R A C T

We present a three-dimensional surface measurement system using imaging fiber endoscope and the measurement is based on the focus technique in uniaxial configuration. The surface height variation of the sample is retrieved by taking into account the contrast modulation change obtained from a projected fringe pattern on the sample. The technique takes into account the defocus change of the fringe pattern due to the height variation of the sample and by a Gaussian fitting process the height reconstruction can be retrieved. A baseline signal procedure was implemented to remove back reflection light coming from the two fiber-surfaces (inlet and outlet) and also a Fourier transform filter was used to remove the pixelated appearance of the images.

The depth range of the system is 1.1 mm and a lateral range of 2 mm by 2 mm. The novelties of the implementation are that the system uses the same imaging fiber as illumination and measurement and offers the advantage of the transportability to the measurement to a confined space having potential application on medical or industrial endoscopes systems. We demonstrate the technique by showing the surface profile of a measured object.

1. Introduction

Applications of endoscopes range from medical, security purposes and industrial inspections. Imaging fiber based systems and endoscope systems present the advantage of portability in small regions where the usage of common imaging systems encounters difficulties. A characteristic of imaging fiber systems is their transportability of the measurement to confined spaces due to the fiber's capability of acting both as a pinhole array and an image-carrying element. The bundle fiber have been characterized to be used with coherent and incoherent light sources [1].

Optical fibers coupled to endoscopes have been used for scanning method based on vibration at resonant frequency [2], for parallel pixels acquisition [3], intensity image caption and also 3D reconstruction using different techniques [4]; some of these techniques are based on hologram interferometry [5], triangulation methods, image shading [6], stereometry, time of flight proposals, optical coherence tomography and structured light projection based systems [7].

On the other hand, uniaxial measurement techniques and imaging fiber based systems presents a good matching due to the fiber property of carrying the illumination and imaging on the same axis, the combination of these two offers an advantage over the common triangulation based techniques specially when objects have discontinuous of height steps, deep holes or the object is placed in confined space, in these cases, uniaxial profilometry techniques are more useful [8–14].

Different methods and setups have been presented using fringe pattern projection based on defocus technique [15] for example: by using a liquid crystal grating with a varifocal lens for projecting the fringes and changing the depth range in a controllable method [8–10]. A complementary implementation is taking into account the non-uniform reflectivity property of the sample surface by measuring at different degrees of defocusing [12]. Other techniques measure the surface depth by analyzing the phase error of a binary pattern [13] and decorrelation of a speckle pattern [14].

In this paper, we propose to combine the focus method with a coherent fiber bundle, which is also called as imaging fiber, to acquire three-dimensional volume information of reflective samples in a uniaxial configuration; the proposed system works as a 3D endoscopic system; This is the main difference from reference [12], in comparison with previous works based on uniaxial measurement [8–13], this is the first implementation where a single imaging fiber is used as illumination system and measurement manner system.

Experimental results about the uniaxial three-dimensional profil-

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http://dx.doi.org/10.1016/j.optcom.2016.12.057
Received 21 September 2016; Received in revised form 16 December 2016; Accepted 22 December 2016
Available online 04 January 2017
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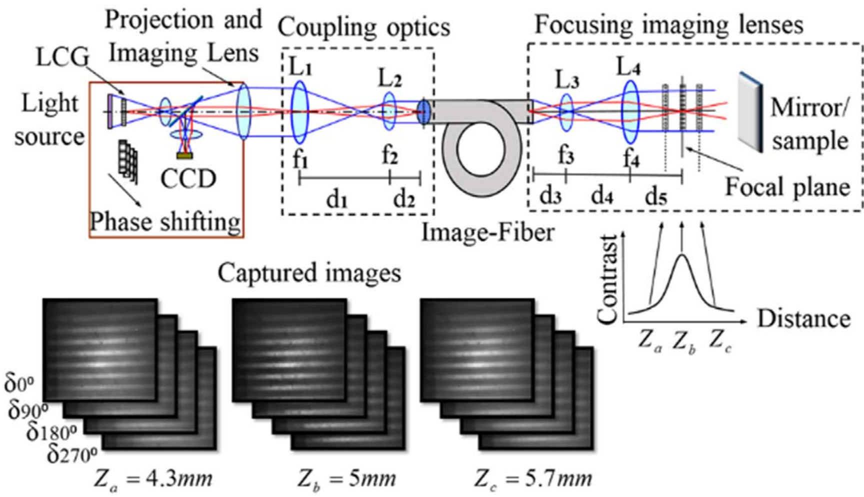

Fig. 1. Optical setup of the 3D profilometer using an imaging fiber in uniaxial configuration. Z_a, Z_b and Z_c represent the captured fringes at different depths.

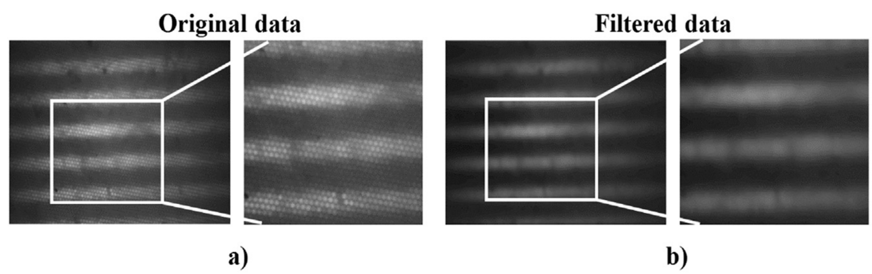

Fig. 2. With the enhancement procedure divided in two parts, is possible to remove the baseline and the pixelated appearance coming from the lenses and the fiber elements respectively. Fig. 2a) and b) shows the original data and filtered data respectively at Z_b=5 *mm*.

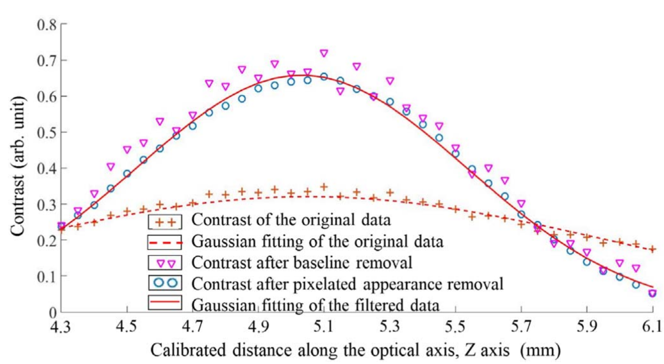

Fig. 3. Comparison between the contrast distributions in the data before and after the two features removal.

ometer using an imaging fiber are shown; In addition, we show how to remove the effects of reflections from the fiber bundle faces and lens surface (baseline) and how to remove the pixelated appearance of the images due to the fiber by a filter on the frequency domain.

2. Theoretical background

The system is based on measuring the contrast variation $\gamma\ (x, y, z_i)$ at each pixel in the image (x, y) at different depth (z_i) using the 4-step phase shifting technique by using a sinusoidal fringe pattern, $I_\delta(x, y) = I_0(1+\gamma(x, y)cos[\varphi_0(x, y) + \delta]$ with controlled parameters: illumination intensity I_0, initial phase $\varphi_0(x, y)$ and controlled phase shift δ. A liquid crystal device is used for generating four intensities $I_{0°}$, $I_{90°}$, $I_{180°}$ and $I_{270°}$ with a relative phase shifting of 90°. Contrast variation can be obtained by a combination of these intensities,

$$\gamma\ (x, y, z_i) = \frac{2\sqrt{(I_{0°} - I_{180°})^2 + (I_{90°} - I_{270°})^2}}{I_{0°} + I_{90°} + I_{180°} + I_{270°}} \tag{1}$$

The contrast distribution along an optical axis approaches to a Bessel function that can be approximated to a Gaussian function [10,14]. The maximum contrast occurs at the imaging plane position of the system. The contrast distribution varies depending on the projection/imaging system and the period of the projected grating pattern. A fitting process on a Gaussian function basis relates the contrast distribution,γ, with depth information, z_i, as:

$$\gamma = \gamma_0 \exp\left(-2\left(\frac{z_i - z_0}{A}\right)^2\right) \tag{2}$$

where γ_0,z_0 and A represent the maximum contrast, location in depth of the maximum contrast and depth range were the 3D reconstruction can be obtained. The Gaussian fitting process will be done by each pixel taking into account uni-axial displacement of the reference mirror. By taking inverse of Eq. (2), depth information can be analyzed for a contrast distribution relation as:

$$z_i = A\sqrt{\frac{1}{2}\ln\left(\frac{\gamma_0}{\gamma}\right)} + z_0 \tag{3}$$

Thus, if we place a 3D object it is possible determine the height distribution from the amount of fringe contrast variation by knowing the fitting parameters γ_0,z_0 and A.

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