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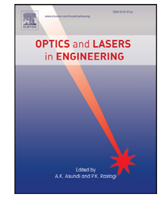

3-D optical profilometry at micron scale with multi-frequency fringe projection using modified fibre optic Lloyd's mirror technique

Arda Inanç[a], Gülşen Kösoğlu[a,b], Heba Yüksel[c], Mehmet Naci Inci[a,*]

[a] Department of Physics, Bogazici University, Bebek, Istanbul 34342, Turkey
[b] Department of Physics, Marmara University, Kadıkoy, Istanbul 34722, Turkey
[c] Department of Electrical & Electronics Engineering, Bogazici University, Bebek, Istanbul 34342, Turkey

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ABSTRACT

A new fibre optic Lloyd's mirror method is developed for extracting 3-D height distribution of various objects at the micron scale with a resolution of 4 µm. The fibre optic assembly is elegantly integrated to an optical microscope and a CCD camera. It is demonstrated that the proposed technique is quite suitable and practical to produce an interference pattern with an adjustable frequency. By increasing the distance between the fibre and the mirror with a micrometre stage in the Lloyd's mirror assembly, the separation between the two bright fringes is lowered down to the micron scale without using any additional elements as part of the optical projection unit. A fibre optic cable, whose polymer jacket is partially stripped, and a microfluidic channel are used as test objects to extract their surface topographies. Point by point sensitivity of the method is found to be around 8 µm, changing a couple of microns depending on the fringe frequency and the measured height. A straightforward calibration procedure for the phase to height conversion is also introduced by making use of the vertical moving stage of the optical microscope. The phase analysis of the acquired image is carried out by One Dimensional Continuous Wavelet Transform for which the chosen wavelet is the Morlet wavelet and the carrier removal of the projected fringe patterns is achieved by reference subtraction. Furthermore, flexible multi-frequency property of the proposed method allows measuring discontinuous heights where there are phase ambiguities like 2π by lowering the fringe frequency and eliminating the phase ambiguity.

1. Introduction

3-D optical profilers have been used over many decades in various areas like medicine [1–3], automobile industry [4–6] and even in underwater applications [7] due to their fast, reliable and non-contact measurement features. Surface profile measurements using fringe analysis have gained more extensive interest over the years starting from 1983 in which Takeda proposed an automatic 3-D shape measurement system [8]. It uses the *Fourier transformation* (FT) to analyse the fringe patterns that are deformed due to the height distribution of the objects. At that time, FT was superior to Moiré pattern projection method, which was firstly used in 1967 by Rowe and Welford [9]. Then, the researchers have used other advanced methods for analysis like *Wavelet Transform* (WT) profilometry [10] and *Phase Shifting Profilometry* (PSP) [11], which are very common techniques nowadays. A historical review about the Fourier and Wavelet transformations can be found in [12]. An extensive review of fringe analysis and projection methods is given in [13].

The analysis methods mentioned in [12] are feasible to apply to both structured light patterns as described in [14–18] and fringe patterns produced by interferometric systems such as *Michelson interferometer* [19], *Fabry-Pérot interferometer* [20], *Linnik interferometer* [21] or very special interferometric techniques as in [22] and [23] where fibre optic cables are used. Structured light patterns are preferred since they provide flexible fringe manipulation according to the needs with the help of software. There are other types of structured light patterns as described in [24–26], which require different analysis techniques than or additional to the aforementioned ones. The designed light patterns in [25] and [26] are especially used to solve the common problem of the phase ambiguities on discontinuous surfaces by marking and colouring fringes. All kinds of structured light pattern methods used in surface profilometry and their extensive comparison are described in [27].

Apart from the advantages of these structured light patterns, they all suffer from some drawbacks and limitations when they are compared with the interferometric methods that use laser sources. The main problem that limits the accuracy of the height measurements is the discrete nature of these digital patterns that stem from projector resolution as stated in [28]. Since the projected pattern has pixels, intensity distribution of the fringes on the object to be measured is not continuous and

* Corresponding author.
E-mail address: naci.inci@boun.edu.tr (M. Naci Inci).

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depends on many factors like object-projector distance, projection angle and camera focus, which affect the accuracy of the system. The proposed method uses optical interferometry and does not have this accuracy limit except the limitation due to the CCD resolution, which exists in all optical profilometric systems.

Since the optical profilometry applications are also widely used in a large range of scales from centimetre to subnanometre [29], it is becoming important to use simple, cheap and compact methods to achieve reasonable precision in desired scales. To extract surface topography at the micron scale, both structured light pattern and optical interferometry based methods must include additional optical elements like lenses in their projection units as in [30] and in [31].

Even though the fringe patterns are easily adjustable for a wide range of fringe frequency in structured light pattern based projection systems by using a computer software, compact interferometry based systems used at micron scale like *Mirau interferometer* and *Linnik interferometer* generally do not have that opportunity since the elements like mirror in the system cannot be modulated easily to produce multi-frequency fringe patterns and they are also highly sensitive to external parameters since they are generally Michelson type interferometers. The limited frequency range is seen in [21] where a compact, Linnik-type interference objective is used for surface profiling. Fringe frequency in this setup is changed discretely by using different light emitting diodes (LED's) that have different wavelengths, which restricts the number of frequencies that can be selected to the number of different LED's available. Additionally, the interferometric systems in [32] and [33], a pair of acousto-optic modulators and an acusto-optic tunable filter are used to produce multi-frequency fringe patterns where these additional devices increase the cost of the optical setup considerably.

In this paper, the projection unit of previously used interferometric system in [34], which uses fibre optic Lloyd's mirror technique, is elegantly modified without using any additional optical elements and is suitably integrated to a compound optical microscope and a CCD camera to study the depth profile of solid objects at the micron scale. In addition to being relatively nonsensitive to the environmental disturbances such as temperature and vibrations and the ability of generating adjustable multi-frequency fringe patterns easily without using any expensive devices as in the digital pattern projection techniques, where the most of the interferometric systems fail, the resolution limitations inherent in the digital projection units do not exist in the proposed technique due to its interferometric nature. As a straight forward calibration procedure, it is preferred to use the microscope stage that can move with known increments. This method is similar to the calibration method mentioned in [35]. There are also some related work that use rigid objects with precisely known dimensions for calibration such as [36]. The technique also possesses the ability to detect phase ambiguities occurred due to surface height discontinuities similar to some of the aforementioned methods, which use structured light patterns. Discontinuous heights with phase ambiguities are successfully profiled using flexible multi-frequency property of the modified Lloyd's mirror assembly, which is simpler to produce and analyse than the coloured or marked structured patterns.

The layout of the paper consists of the description of the intensity function produced by the fibre optic Lloyd's mirror technique, the elaborate theory of the 1-D Continuous Wavelet transformation used to analyse phase of the produced fringe patterns and the phase to height conversion method, experimental details related to the proposed modification, image acquisition and calibration, results and discussion, which is followed by suggestions for possible improvements as a future work.

2. Theoretical background

2.1. Fringe intensity

Intensity analysis of the Lloyd's mirror is very similar to Young's double slit experiment but there is an extra π phase difference between the light beams due to the reflection from mirror. As seen in Fig. 1, D is the distance between the source and the screen that the fringe patterns are projected on and d is the separation between the real and the virtual fibre. By using the virtual fibre as the second source and assuming $D \gg d$, we draw a line (black), which is nearly parallel to the lower beam. It starts from the middle of the sources and goes to the point on the screen where the interference occurs. From the similar triangles, the angle between the mirror and the drawn line is found to be θ and the path length difference s is approximated as $s \approx d\sin\theta$. To convert the path length difference to phase difference, s is multiplied by $2\pi/\lambda$. Additionally using the small angle approximation, $\sin\theta \approx \theta \approx \tan\theta$, and $\tan\theta = x/D$, one dimensional (1D) intensity signal produced by the fibre optic Lloyd's mirror technique on a flat screen is expressed as

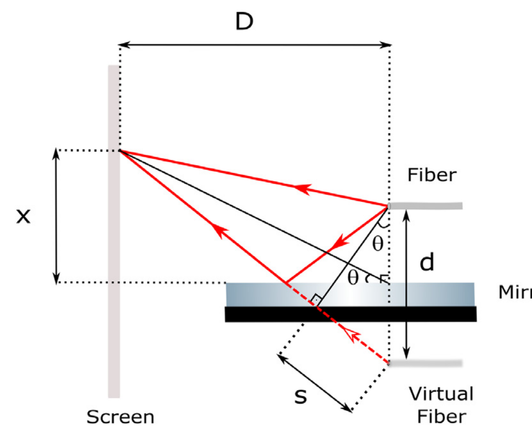

Fig. 1. Fibre optic Lloyd's mirror assembly.

$$I(x) = I_0(x)\left[1 + V(x)\cos\left(\frac{2\pi d x}{\lambda D} + \pi\right)\right] \quad (1)$$

where $I_0(x)$ represents the background noise, $V(x)$ is the fringe visibility. The relationship between the distance moved and the frequency change is assumed to be linear according to the relationship $d/\lambda D$, which is given with Eq. (1), since the distance between the fibre tip and the screen is much larger than the separation between the fibre and the mirror, i.e; $D \gg d$. The term $d/\lambda D$ is equal to the carrier frequency, f_0, of the projected fringe pattern on the flat screen. Changing d produces fringes with different f_0 frequencies. Even though f_0 is assumed to be a constant here, any linear or nonlinear terms in it due to the projection angle or nonlinearity in the laser source are eliminated during the carrier removal, which utilizes a reference subtraction technique [37]. Furthermore, since it is the same for every y value, 1D intensity signal is extended to two dimensions (2D) and the deformed phase term $\phi(x, y)$ caused by the height of the test object is added to derive the intensity signal as

$$I(x, y) = I_0(x, y)\left[1 + V(x, y)\cos(2\pi f_0 x + \pi + \phi(x, y))\right] \quad (2)$$

To recover the phase of a row of the image, the carrier frequency f_0 should satisfy the following condition [38]:

$$2\pi f_0 > \left|\frac{d\phi(x)}{dx}\right|_{max} \quad (3)$$

However, since extracted 2D signal is processed row by row for every y value, 1D version of Eq. (2), denoted as $I(x)$, is used throughout the phase analysis part.

2.2. Phase analysis

To analyse the intensity signal in Eq. (2), WT is used . As opposed to the FT analysis, WT analysis is more noise insensitive since FT processes a signal globally, whereas WT uses the local features of the wavelets [39]. In FT, also the number of fringes on the analysed image should be integer to prevent leakage from the borders and the deformed intensity