Novel techniques for random depth access three-dimensional white-light optical metrology

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ABSTRACT

Digital stepping is desirable in optical metrology—operation is simple, absolute position is known, and random regions of interest can be skipped to, rapidly and accurately. However, in white-light interferometry, analog scanning has traditionally been employed because, in one operation, it achieves depth scanning of a sample and an electronically detectable optical carrier through a Doppler shift. This is not obligatory nor efficient in functional machine vision, especially if approximate preknowledge of the sample exists. Two methods, utilizing digital depth stepping and a superluminescent diode, are presented to decouple optical carrier generation from depth scanning in full-field white-light interferometry. One technique employs a complementary metal-oxide semiconductor camera and acousto-optic modulation to generate a frequency difference between two arms of a Mach–Zehnder interferometer. The other technique uses a Michelson interferometer with a piezoelectric transducer integrated to the digital stepper motor to facilitate analog scanning and an optical carrier of 4 periods, sampled with a standard charge-coupled device camera. In the former case, random depth access measurement of an engineering gauge block calibration sample is presented, while the latter demonstrates the application of the random depth access full-field white-light interferometry to a small punch test. A further benefit of these techniques is the possibility of interferometric phase retrieval on condition of path length matching; this is proven by the implementation of a heterodyne phase retrieval algorithm in the gauge block measurement. Both techniques represent an advance in optical metrology, offering an inexpensive and functional solution to machine vision and industrial measurement applications.

Keywords: white-light interferometry, three-dimensions, random access, functional machine vision.

1. INTRODUCTION

Although aesthetically appealing, optical measurement is often superseded by simpler, less expensive, and easily adaptable mechanical measurement methods. Small punch testing\textsuperscript{1, 2} is an example of this where, for over two decades, optical measurement has not been comprehensively applied. Typical techniques use a linear variable differential transformer (LVDT),\textsuperscript{3} the displacement of the test machine,\textsuperscript{4} or extensometer\textsuperscript{5} to measure the resulting sample displacement for a known applied force. The first inroads optical measurement was the use of a borescope with white light imaging was utilized to detect the onset of sample cracking,\textsuperscript{6} but this was for visual inspection not measurement. A three-dimensional optical measurement technique has yet to be demonstrated for the small punch test.

The reason for this is that optical techniques often require excessive complexity or expense to perform the metrology. White-light interferometry\textsuperscript{7} (WLI) offers micrometer profilometry, but conventionally linear analog scanners have been used to scan a sample in depth.\textsuperscript{8, 9, 10} This is often unnecessary; in a small punch test it is feasible to know before measurement what the sample deformation is. It is inefficient to scan an entire sample profile, if there is good preknowledge.

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Figure 1. Experimental setup. Components include: superluminescent diode (SLD), optical fiber (OF), collimating lens (COL), 50/50 beamsplitters (BS1, BS2, BS3, BS4), variable attenuator (ATT), polarizer (POL), acousto-optic modulators (AOM1, AOM2), camera objective (CO), CMOS-DSP camera (CAM). The reference (REF) was a plane mirror. The sample (SMP) was a polished metal gauge block.

2. METHODOLOGY

2.1. Full-field heterodyne WLI

2.1.1. Optical setup

The optical setup, shown in Figure 1, utilized a Mach–Zehnder interferometer, with an AOM* in each arm, slightly rotated off-perpendicular so that the Bragg angle was met. The AOMs were integrated in a phase locked-loop, as shown in Figure 2; one driven at 80 MHz and the other at a frequency 80 + \( f \) MHz, where the beat (carrier) frequency \( f \) between both arms was capable of steady locking from 3–1000 Hz. The light source† was a 830 nm SLD with a full-width at half-maximum bandwidth of 22 nm and supplied 4.89 mW with a collimated beam diameter of approximately 2 mm. The reference mirror was translated on a digital stepper motor‡ with a stepsize resolution of 100 nm.

2.1.2. Sample specification

The sample was specifically chosen to present the dual functionality of the technique, that is, random depth access full-field WLI plus full-field phase retrieval. With approximate preknowledge of the sample it was possible

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*Model 3080-151, Crystal Technology Inc., Palo Alto, CA USA.
†OLSLD-82-HP1, Opto-Link Corporation Ltd., Hong Kong, PRC.
‡UTM Series, Micro-Controle SA, Evry Cedex, France.
to step directly to an estimated surface location in depth, then step through the coherence envelope. On locating the coherence envelope, at a fixed position inside, full-field phase retrieval was implemented.

The sample used was composed of two standard engineering gauge blocks, of a polished metal surface. A plane mirror acted as a back plate, with two gauge blocks (of heights 1.00 mm and 1.05 mm) placed on top, side by side approximately 1 mm apart. The sample technical specification is depicted in Figure 3. A measurement of the 1.05 mm gauge block, taken with an industrial profilometer\(^5\), appears in Figure 4 with a zoom view, where it is evident that the gauge block is flat within 300 nm, which is unresolvable with the 14 μm axial resolution of white-light interferometry with the SLD light source.

The first-order diffracted beam from AOM1 was directed towards the surface of the sample where the measurement was made, while the zero-order beam was unused. The experimental situation is shown in Figure 5 in a 512 × 512 pixel camera image where it is shown that the first order diffracted beam was targeted at the spacing between the two engineering gauge blocks.

### 2.1.3. Experimental settings

**White-light profilometry** To demonstrate the micrometer profiling capability of WLI and random spatial acquisition of the logarithmic CMOS camera\(^6\), three 128 × 1 pixel ROIs were simultaneously accessed on the CMOS sensor of the camera 1024 times at a rate of 1106 Hz, with \(f_c = 50\) Hz. The reference mirror was stepped with the digital stepper motor in 1 μm steps, thus each pixel sampled a cw signal when a sample surface and reference mirror had a path length difference inside the coherence length of the light source. A relatively large range of depth (950 μm) was skipped, due to having approximate preknowledge of the sample, and one feature of this technique is the ability to access random ROIs in depth. The degree of coherence was evaluated by calculating the ac rms value of the cw signal, since it gave an accurate estimate of the amplitude of a cw signal while averaging random noise. More discussion of ac rms and cw amplitude is given in Section 2.3.1.

**Full-field heterodyne interferometry** By stepping the reference mirror to a position where the path lengths of the reference mirror and one of the sample surfaces were matched within ±1 μm corresponding to a maximum value of the WLI ac rms envelope, at a fixed position phase retrieval of the interferometric signal from each pixel was implemented. A 32 × 32 pixel ROI on the gauge block was sampled 1024 times at a rate of 431 Hz, with \(f_c = 25\) Hz. The camera data were downloaded to an external PC for postprocessing. Details of the heterodyne phase retrieval algorithm is given in Section 2.3.2.

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\(^5\)Alpha-Step IQ, KLA-Tencor Inc., San Jose, CA USA.

\(^6\)iMVS-155, AKAtech SA, Ecublens, Switzerland.
2.2. Full-field step-and-scan WLI

2.2.1. Optical setup

In an optical setup employing a Michelson interferometer as shown in Figure 6, the sample was illuminated with a 10 mm diameter collimated SLD light beam of 5.0 mW power. The PZT-DSM combination actuator allowed random depth access: stepping the DSM selected the depth of interest (50 nm stepsize), the PZT was linearly scanned with an analog voltage to generate the optical carrier. As force, $F$, was applied to the disk, the displacement profile was measured at prechosen depths selected by the DSM.

2.2.2. Sample specification

The sample was a rough mild steel disk, of 80 mm diameter and 525 μm thickness, having a Young’s modulus of $E = 206 \times 10^9$ N/m$^2$, and yield stress $\sigma_y = 239 \times 10^6$ N/m$^2$. As force was applied to the disk, the full-field displacement profile was measured at prechosen depths selected by the DSM. It should be noted that through experimentation, it was found that the sample finish was important. A sandpaper finish gave good interferometric visibility with small displacement, however as the sample was increasingly displaced, the interferometric visibility degraded. The sandblasted finish, see Figure 8, gave the best results over all sample displacement. The reason for this is that a rougher surface gives a better speckle field.

2.2.3. Experimental settings

The test machine recorded the applied load and crosshead position. The test fixture was integrated with two geometrically opposite LVDTs, as elucidated in Figure 7, which provided an accurate measurement of the sample displacement. Furthermore, the sample was clamped with six axisymmetric screws and a ball bearing ring was intended to self-stabilize the applied force, and achieve ideal vertical force applied to the sample under test.

A single LabVIEW VI controlled the entire experiment. The experimental algorithm is outlined in Figure 9, with the associated LabVIEW controlled PC resources. A force was applied to the sample under test. At each 10 μm depth step the PZT was linearly scanned, with an analog sawtooth voltage, over $2\lambda \approx 1.7\mu m$. This gave an intensity cw signal of 4 periods, on condition of interferometric path length matching. Triggered by the bottom of the PZT sawtooth, the full-field image was sampled with the 512 × 512 pixel CCD camera operating at 30 Hz. The ac rms value was calculated to estimate the amplitude of the cw signal.

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MoCo Stick, Micos GmbH, Eschbach, Germany.

*Intron 4444, Intron Corporation, Norwood, MA USA.

†PCI-1200, PCI-GPIB, IMAQ PCI-1405, National Instruments, Austin, TX USA.
2.3. Signal processing

2.3.1. Periodic sampling systematic error

A useful estimation of the amplitude of the cw signal is to take the ac rms defined for a \( N \) point sampled cw signal \( x(n) \) as

\[
\sigma = \left[ \frac{1}{N} \sum_{n=0}^{N-1} \left( x_n - \bar{x} \right)^2 \right]^\frac{1}{2},
\]

where the mean is

\[
\bar{x} = \frac{1}{N+1} \sum_{n=0}^{N-1} x_n.
\]

A source of error on the ac rms estimate occurs when the number of periods over which the samples are taken is not an integer. Independent of offset, frequency, and static phase, the ac rms amplitude of a noiseless, unit amplitude cw signal is analytically defined as

\[
\sigma_a = \left\{ \int_0^P \left[ \cos(2\pi t) \right]^2 dt \right\}^\frac{1}{2},
\]

where \( P \) is a real number variable expressing the number of cw signal periods. The resulting integral is

\[
\sigma_a = \frac{1}{\sqrt{2}} \left[ 1 + \frac{1}{4\pi P} \sin(4\pi P) \right]^\frac{1}{2}.
\]

Since the maximum value of \( \sin(x) \) is 1, the relative ac rms error is upperbounded by

\[
\sigma_{UB} = \frac{1}{4\pi P}.
\]

This error is not overly significant, for example with at least 4 periods it is less that 2%, while over approximately 46 periods, systematic error due to nonperiodic sampling of the cw signal is negligible at < 0.11%. Systematic
nonetheless, it can be reduced by tapering, that is, multiplication of the cw signal by a Hanning window and scaling factor. However this comes at the cost of significant processing time, and a 20% reduction in random noise averaging. Tapering was not implemented for the results reported here.

2.3.2. Heterodyne phase retrieval algorithm

Heterodyne interferometric phase measurement\textsuperscript{15} can be applied to WLI, if the path lengths of the interferometer arms are matched at a fixed position within the coherence length of the light source. The optical carrier can be generated by acousto-optic modulation or by a step-and-scan method using a DSM-PZT. Unlike phase-shifting algorithms,\textsuperscript{16} heterodyne phase retrieval uses analytic signal properties to retrieve the phase of a cw signal. The algorithm tradeoff is increased accuracy at the cost of processing time. For the full-field heterodyne WLI measurement presented here, it is worth noting that the phase measurement is instantaneous over a full-field in with 1024 samples in less than 2.5 seconds which reduces effects of thermal drift. There is no electromechanical movement during the measurement, unlike typical stepping techniques, which reduces errors due to vibrations. Furthermore, there is no cumbersome electromechanical stepsize calibration or errors due to incorrect phase-shifting.

Algorithm principle The intensity signal from a $xy$\textsuperscript{th} pixel can be represented as

$$s_{xy} = a_{xy}(t) + b_{xy}(t) \cos [2\pi f_c t + \psi_{xy}(t) + \phi_{xy}],$$

where $a_{xy}(t)$ and $b_{xy}(t)$ take into account light intensity modulations, $\psi_{xy}(t)$ is the phase changes due to carrier frequency modulation, translational vibrations and drifts, $f_c$ is the carrier frequency, and $\phi_{xy}$ is the static phase. In full-field interferometry, the difference in $\phi$ between two adjacent pixels is a measure of the path length difference, modulo-$2\pi$ corresponding to $\lambda/2$, where $\lambda$ is the wavelength of the light source. The analytic signal of Equation (6) is obtained by applying a bandpass filter with negative frequencies zeroed, and expressed for a 0\textsuperscript{th} pixel as

$$s_{a0} = \frac{b_0(t)}{2} \exp \{j [2\pi f_c t + \psi_0(t) + \phi_0] \}. \quad (7)$$

The analytic signal of an adjacent pixel is

$$s_{a1} = \frac{b_1(t)}{2} \exp \{j [2\pi f_c t + \psi_1(t) + \phi_1] \}. \quad (8)$$

Dividing Equation (8) by Equation (7) gives

$$\Phi = \frac{b_1(t)}{b_0(t)} \exp \{j [\psi_1(t) - \psi_0(t) + \phi_1 - \phi_0] \}. \quad (9)$$
Step to position \( z = 0 \) μm

- RS-232

Read test machine

- GPIB

Apply force

- GPIB

Scan PZT 2 λ

- DAC PCI-1200

Acquire \( N = 30 \) CCD frames

- IMAQ PCI-1405

Step increase \( z = 10 \) μm

RS-232

Yes

No

Figure 9. Punch test measurement LabVIEW algorithm.

\[ s_{pi}(t) \]

2D conv.

\[ s_{pi} \rightarrow \text{div.} \]

\[ \phi \rightarrow \Delta \phi \rightarrow \text{YES} \]

\[ \Delta \phi \]

\[ \text{cw signal} \]

\[ \text{Hann}_2 \text{window} \]

\[ s_{pi} \]

\[ f \]

\[ f \]

\[ s \]

\[ a \]

\[ \Phi_n \]

\[ \Delta \phi \]

\[ \psi_1(t) \]

\[ \psi_0(t) \]

\[ \phi_1 \]

\[ \phi_0 \]

\[ \psi_1(t) - \psi_0(t) + \phi_1 - \phi_0 \]

Figure 10. Heterodyne phase retrieval block diagram.

and the instantaneous phase difference between the two pixels is the argument of Equation (9), and taking the mean of the argument over \( n \) samples further increases the accuracy of the static phase difference

\[
\Delta \phi = \frac{1}{n} \arg(\Phi_n) = [\psi_1(t) - \psi_0(t) + \phi_1 - \phi_0],
\]

where in the case of spatially uniform temperature changes and translational vibrations, and instantaneous measurement of static and vibrational induced phase eliminating the vibrational term; \( \psi_1(t) \approx \psi_0(t) \). A two-dimensional phasemap is obtained by taking the intensity signal from a single pixel as a reference and calculating the static phase difference between this reference and every other pixel intensity signal.

The algorithm is explained diagrammatically in Figure 10. To implement the algorithm a Hann\(_2\) window was built of length equal to 4 periods of the cw signal. This window is constructed by convolving a Hanning window with itself in time. The window being symmetrical about \( t = 0 \) had a mathematical expression for \( 0 \leq f_c t/2 \leq 1 \) of

\[
h(t) = \left[ 1 + \frac{1}{2} \cos \left( \frac{2\pi f_c t}{2} \right) \right] \left[ 1 - \frac{f_c t}{2} \right] + \frac{3}{4\pi} \sin \left( \frac{2\pi f_c t}{2} \right).
\]

The Hann\(_2\) window was multiplied by \( \exp(j2\pi f_c t) \), to center the passband of the filter spectrum on the positive carrier frequency of the cw signal, and attenuate negative frequency component. The Hann\(_2\) window being equal to 4 periods gives the algorithm tolerance for slight carrier frequency variations. The full-field intensity cw signal from each pixel of the ROI was convolved with the Hann\(_2\) window. The resulting signals were divided by a reference pixel signal, and the static phase difference was calculated by the taking the argument, as per Equation (9) and Equation (10), respectively.

**Negative frequency attenuation** The Fourier transform of the Hann\(_2\) window of Equation (11) is defined as

\[
H(f) = \left[ \frac{1}{x^2 - 1} \sin(\pi x) \right]^2,
\]

where

\[
x = \frac{2(f - f_c)}{f_c}.
\]

For \( f < 0 \), the variable \(|x|\) becomes larger than 2 and hence, Fourier transform of the Hann\(_2\) window in Equation (12) decreases with an upper bound of

\[
H_{UB}(f) = \left[ \frac{1}{\pi x (x^2 - 1)} \right]^2,
\]
which is always smaller than 0.003. Furthermore, at the negative carrier frequency $f = -f_c$, the variable $x = -4$ and the upper bound on Equation (12) is $28.15 \times 10^{-6}$.

**Simulation of algorithm** Considering $p = 64$ signals, each of 30 periods, of $N = 1024$ samples, of static phase $\phi = 0$, and linear varying phase $\psi(p)$, the simulated signals are expressed as a vector size of $N \times p$, that is

$$x = \cos [2\pi f_c n + \phi + \psi(p) + n\epsilon],$$

(15)

with

$$\psi(p) = 0, \frac{1}{63} \pi, \frac{2}{63} \pi, \ldots, \frac{\pi}{4},$$

and arbitrary static phase $\phi$ the same for each signal and uniformly distributed noise in the range $-0.04 \leq n\epsilon \leq 0.4$. A single simulated noisy cw signal from Equation (15) is shown with the Hann$_2$ window in Figure 11, with corresponding spectra. Note that the Hann$_2$ window spectrum passes the positive cw signal (centered at 50 Hz), whilst the negative frequency component is heavily attenuated, due to the sharp numerical rolloff of the Hann$_2$ window; in the ideal case, the negative frequency component is zeroed. The Hann$_2$ window is built to a width of 4 periods of the cw signal, this has two benefits: (a) it allows for some fluctuation of the cw signal carrier frequency, evident in the spectral plot of Figure 11, and (b) over more that 4 periods the convolution result can be averaged to increase accuracy.

Firstly, although not shown, without noise added to the cw signal, simulations gave a phase error std in the arbitrary computer error range $10^{-15}$. It is evident in Figure 12 that the retrieved phase has considerably more error than the noiseless simulation. Nonetheless, with $|2\pi| = \lambda/2$, a std phase error of $5.0 \times 10^{-3}$ represents an accuracy of some 330 pm.

**2.3.3. WLI envelope peak detection by crosscorrelation**

To improve the accuracy of a depth measurement, the crosscorrelation of two WLI envelopes from two interfaces can be used to determine the distance between the envelopes. Crosscorrelation of two sequences, $x$ and $y$, is defined as

$$\Gamma_{xy}(n) = \sum_m x(m-n)y(m).$$

(16)

If the two sequences $x$ and $y$ represent either WLI signals or envelopes located at two difference positions of the path length scanning, the peak in the crosscorrelation function, with respect to the autocorrelation of either sequence, corresponds to the precise distance between the two peaks.

**Figure 11.** Noisy cw signal and spectrum with Hann$_2$ window.

**Figure 12.** Phase error from noisy cw signal.
The punch test volumetric profile, built by successive depth \( (z) \) stepping and PZT scanning, can be sliced in various \( x-y \) planes and an averaged cross-sectional profile of the sample deformation can be constructed. The amplitude of the cw signal on a single pixel follows a WLI envelope as the interferometer path lengths are matched and the reference arm is stepped in depth. The WLI envelope peak corresponds to exact path length matching and to accurately determine where the peak occurs, crosscorrelation was utilized. For a single \( x-y \) slice, a reference \( z \)-vector \( (z_0) \) was cross-correlated with all other \( z \)-vectors \( (z_{xy}) \), and the location of the peak of the crosscorrelation product vector gives an accurate estimate of where the peak of the WLI envelope on vector \( z_{xy} \) occurs, with reference to vector \( z_0 \).

### 3. RESULTS AND DISCUSSION

#### 3.1. Full-field heterodyne WLI

##### 3.1.1. True random access profilometry

The full-field WLI profile measurement for one of the 128 × 1 ROIs is shown in Figure 13, where 1 pixel translates as approximately 40 \( \mu \)m on the sample. The ac rms on each pixel is plotted as a function of depth \( (z) \) and pixel \( (x) \) scans. At \( z = 0 \)\( \mu \)m, interference on the 1.05 mm gauge block was achieved on some of the pixels on the ROI. At \( z = 50 \)\( \mu \)m, interference was achieved on the 1.00 mm gauge block on some pixels. At \( z = 1050 \)\( \mu \)m, interference was achieved on the mirror, that is, the area in between the gauge blocks.

The surface position was given by the position of the stepping motor for which the ac rms value of the intensity signal is maximum. For this reason no attention was paid to the amplitude fluctuations from one pixel to other evident in Figure 13. The amplitude fluctuations are due either to the nonuniformity of the light beams or of the CMOS sensor sensitivity. The effect of both factors as well as the beam phase nonuniformity could be corrected by normalization on a reference mirror replacing the sample. The normalization process is not described because the limited paper length and limited improvement that it adds to the demonstration of the system performance.

##### 3.1.2. Nanometer surface relief

Sampling at \( f_s = 431 \) Hz on the CMOS camera, an experimental cw signal is shown in Figure 14, with the Hann_2 window designed at 4 periods. The retrieved phasemap of the 32 × 32 pixel ROI, shown in Figure 15, gives a full-field profile of the surface of the 1.05 mm engineering gauge block with nanometer resolution, where 1 pixel corresponds to approximately 40 \( \mu \)m on the sample. The measurement involved no electromechanical scanning, and the acquisition time was 2.38 seconds.
Figure 15. Heterodyne phase measurement of gauge block surface.

Figure 16. Normalized experimental cw intensity signal.

Although the axial resolution of the WLI profiling (14 µm) is impressive, it is incomparable with nanoscale interferometric phase measurement of Figure 15, where measurement smoothness and quality assessment of the surface is possible on a scale unobtainable with conventional WLI methods. However, the combination of full-field WLI with heterodyne phase retrieval, offers unique functionality and a relatively large range. The axial resolution in effect acts as depth selection for an interferometric phase retrieval measurement. An arbitrary plane of interest over a relatively large depth, for example 1.05 mm can be selected within the 14 µm coherence length of the light source, and at this depth full-field phase retrieval giving nanometer resolution is achievable.

3.2. Full-field step-and-scan WLI

3.2.1. Full-field profilometry

With 4 periods of the cw signal sampled at $f_s = 30$ Hz with the CCD, the punch test experimental signal is shown in Figure 16. The gradual volumetric deformation of the sample is shown in Figure 17. The volumetric visualization is useful in assessing uniform sample deformation, which with conventional punch test methods goes unchecked. However, assuming sample deformation is axisymmetric, the volumetric profile is excessive: a cross-sectional profile is more practicable.

It is worth noting that using the 4 period cw signal full-field heterodyne phase retrieval is possible with this step-and-scan technique. Outside of simple surface morphology, such application allows simple and accurate calibration of the applied force, that is, as initial force in applied causing sample deformation on the nanoscale, if the force is applied uniformly the correlated phase should produce circular interference fringes.

3.2.2. Averaging profile cross-section

The cross-sectional profile is shown in Figure 18 for different applied force. The sample surface is precisely located by taking the point of maximum light intensity variation for a given pixel for all depth steps using crosscorrelation as discussed above. Averaged over 10 slices of the volumetric profile, from the cross-sectional profile maximum displacement can be estimated and knowing the force, the important force–displacement curve can be obtained.

Although small punch test profiling has been demonstrated at incremental 10 µm depth steps with full-field imaging, such numbers of measurements (100 for 1 mm deformation) should not be necessary. This technique allows random access in depth, and with approximate preknowledge of the sample profile, for example from the LVDTs and crosshead position, it is possible to step to a number of prechosen depths, for example 5–10, and from these 5–10 profile rings curve-fit their averaged cross-section. Furthermore, with the CMOS-DSP camera used in previous chapters, it is feasible to sample lines of interest and create an averaged cross-sectional profile from 5–10 lines of pixels. Thus, a truly functional random access measurement system is realizable.
Computational requirements of the heterodyne phase retrieval algorithm might be undesirable. The PZT of the system lends itself to an argument for phase-shifting algorithms and electronic speckle pattern interferometry (ESPI) techniques. However, with the white-light source, interference can be burdensome to achieve, and if the sample is deformed, full-field ESPI will not be possible. If there was the possibility to switch between coherent (helium–neon) and white-light (SLD) a hybrid interferometric system becomes tangible—micrometer three-dimensional profilometry by WLI and full-field phase measurement of nanometer displacement within $2\pi$ by ESPI.

4. CONCLUSIONS

To conclude, a new approach to full-field optical metrology has demonstrated random depth access white-light interferometry through precise digital stepping and acousto-optic modulation. Furthermore, the technique allows full-field interferometric phase retrieval at random ROIs in depth without electromechanical scanning. Position in depth is controlled within 100 nm by a digital stepper. Depth range was demonstrated as 1 mm, but in practice larger depths (100 mm) should be possible depending on stepper range. The system features no analog scanning using acousto-optic modulation for optical carrier generation, and a digital stepper selects the depth plane of the measurement. Full-field heterodyne WLI provides a method for inexpensive yet functional high precision three-dimensional machine vision. Applications include material surface characterization, microfluidics, and possible adaption to optical coherence tomography.

The application of random depth access step-and-scan full-field WLI to a small punch test has been demonstrated. The technique enables fast full-field profilometry and random access in depth. Advantages over mechanical measurement methods include noncontact full-field measurement, averaged cross-sectional profiling, uniform deformation analysis, and applied force calibration. Whereas conventional punch test measurement methods have relied on the force versus maximum displacement curve, higher quality and more comprehensive experimental data is obtained through this approach. Future work will attempt to relate cross-sectional material deformation curve-fitting with established computational mechanics models and investigate a white-light and ESPI hybrid measurement system.

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REFERENCES


