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Multi-lambda digital holography with auto calibration of temporal phase-shifts and synthetic wavelengths

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Abstract: A fast auto calibration method for (lensless) multi-wavelength digital holography with arbitrary temporal phase-shifts is presented. The calibration algorithm is simple to calculate and needs just one additional image acquisition per wavelength.
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Introduction

Application of digital holography to sophisticated industrial measurement tasks is often restricted by phase ambiguities due to the limited wavelength and the resulting restriction of the dynamic range. Spatial unwrapping can overcome this problem but often fails at steep edges. Furthermore coherent illumination of optically rough surfaces generates a speckle pattern with statistically equally distributed phase and therefore shape measurements on the basis of the reconstructed phase map are not possible. To overcome both restrictions digital holograms at multiple wavelengths are recorded and evaluated. Moreover reconstruction of disturbing terms such as twin image and zero order is avoided by temporal phase shifting. For this purpose the temporal phase steps usually have to be controlled carefully. To keep the setup simple we use an efficient algorithm [1] to calculate phase differences between subsequently recorded interferograms which was presented last year [2]. Because the knowledge of the generated synthetic wavelength (s. Eq. 1) has strong influence on the measurement accuracy we developed a simple and efficient method to measure the synthetic wavelength directly.

Experimental setup and hologram recoding

Figure 1 shows an experimental setup for lensless digital holography. A tunable diode laser with external cavity (Toptica DL100) is used as illumination device [3]. The wavelength of the diode laser is tuned by tilting an external grating. To avoid beam misalignment due to the tuning the beam is coupled into a single mode fiber. To guarantee mode-hop free operation during the measurement and to monitor the actually emitted wavelength a spectrum analyzer is applied. After having passed the glass fiber the light is collimated and divided into an object and reference wave. Both are expanded at least to the size of the object. The reference wave is guided by a mirror that is mounted on a piezo stage to realize temporal phase shifts between object wave and reference wave. The piezo stage is running in open-loop mode.

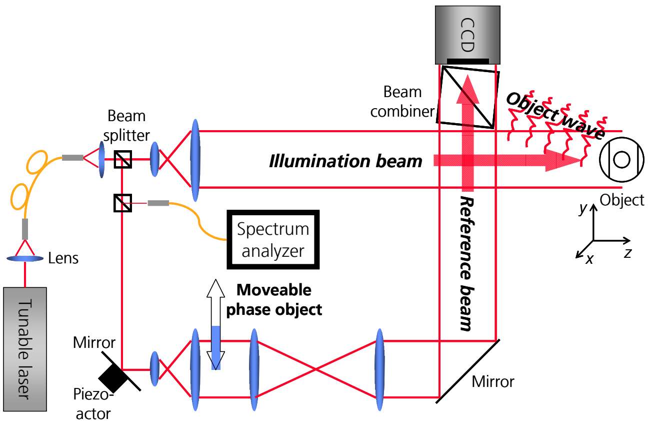

Figure 1: Experimental setup for temporal phase-shifting lensless multi-lambda digital holography with moveable reference object (d=3.0 mm, BK7 glass plate)

Additionally, a movable phase object is located in the reference path to measure the generated artificial wavelength directly as described below. It is illuminated by the expanded reference beam and imaged onto the CCD sensor. Finally the reference wave and the diffracted object wave – usually a speckle pattern – are superimposed by a beam combiner. The spatial intensity distribution of the generated digital hologram is captured by an 8 bit CCD camera with 1394 x 1040 pixels, 4.65 µm pixel-pitch and IEEE1394 interface (AVT Marlin).

To perform shape measurement with the described setup appropriate wavelengths λ_1, λ_2, ...– minimum two – have to be chosen to generate at least one artificial wavelength. The typical linewidth of the diode laser is specified to be between 0.5 MHz and 1 MHz. The minimum artificial wavelength is restricted by the tuning range of approximately 8 nm while the maximum is restricted by the spectral stability of the system and the repeatability of the tuning unit (tilt of the external grating, diode current and temperature control). With it repeatable generation of artificial wavelengths from app. 75 µm up to several centimeters is possible.

For every wavelength λ_i (i=1, 2, ...) three phase-shifted holograms of the same object state without reference object and between one and three additional images (algorithm dependent) with the moveable phase object shifted into the reference beam are recorded (s. Fig. 2c and d). A comparison between different algorithms will be given in the oral presentation.

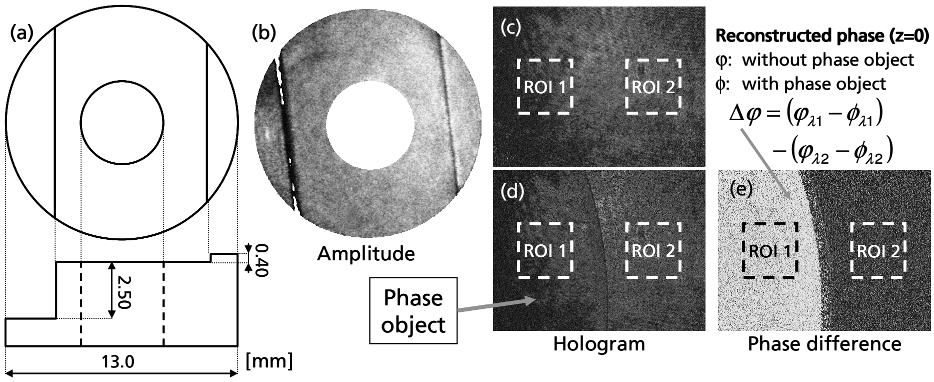

Figure 2: (a) Drawing of the test object (shim with two cut-outs of different height); (b) Reconstructed amplitude (speckle pattern) of the test object; (c) Hologram of the test object (d) with additional phase object on the left side of the image; (e) Difference phase image of the generated artificial wavelength (phase object on the left side)

Numerical Reconstruction and Auto Calibration Method

Numerical reconstruction of the object wave is performed in three steps. First of all a general method [1] to extract the arbitrary unknown and unequal phase steps between the recorded interference patterns is applied. Thereby phase steps are calculated based on the statistical nature of the diffraction field. This method is simple, highly accurate and usable for any frame number N (N > 3) and for both reflecting and diffusing object surfaces. Subsequently the complex object wave within the hologram plane – amplitude and phase – is reconstructed by application of the calculated phase steps to a temporal phase shifting algorithm [1][2]. Finally, propagation of the complex object wave to (multiple) planes is performed by computation of a numerical approximation of the Fresnel-Kirchhoff diffraction integral [4].

Furthermore, difference phase images (modulo 2π) are calculated by subtracting reconstructed spatial phase distributions of the same object state and reconstruction distance from each other. The resulting difference phase distribution corresponds to an interferogram that would be observable if illumination was performed with a wavelength equal to the artificial wavelength which is given by:

$$\lambda_a = \frac{\lambda_1\lambda_2}{|\lambda_1 - \lambda_2|} = \frac{\lambda_1\lambda_2}{\Delta\lambda} \qquad (1)$$

Thereby λ_i (i=1, 2, ...) denote the individual wavelengths of the recorded holograms. Multiple artificial wavelengths are used to avoid unwrapping errors, e.g. at steep edges or deep holes [2][6].

The accuracy of the knowledge of the difference between the wavelengths in the denominator in equation 1 has strong effect on the artificial wavelength and therefore to the measurement. To generate artificial wavelength in the range of several millimeters it is necessary to measure $\Delta\lambda$ with an accuracy of app. 0.001 nm. The precision of the applied spectrum analyzer is Δ_λ=0.005 nm. To improve measurement accuracy of the artificial wavelength we applied a moveable phase object (BK7 glass slide, d=3.0 mm, n_{BK7}=1.51118 @ 780 nm) to the reference path of the setup. To calculate the phase shift $\Delta\varphi$ induced by the glass slide, the mean value of two regions of interest (ROI 1 and 2, s. Fig. 2) are evaluated. With the knowledge of its thickness d and refractive index n_{BK7} it is possible to calculate the artificial wavelength directly from equation 2.

$$\lambda_a = \frac{2\pi}{\Delta\varphi} d(n_{BK7} - n_{air}) \qquad (2)$$

Using Cai's 4-step algorithm [1] only one additional image with phase object in the reference path has to be acquired. But it has to be assured that phase shifts between subsequent images of both ROIs are smaller than π.

Alternatively, it is possible to capture three additional phase shifted holograms with the phase object in the reference path and perform reconstruction also with Cai's 3-step algorithm [1]. Then the difference (mod 2π) between the reconstructed phase in the hologram plane with and without phase object is calculated for each wavelength and subtracted from each other. The outcome is the reconstructed phase object at the requested artificial wavelength. Insertion of the averaged phase difference $\Delta\varphi$ between ROI 1 and 2 (s. Fig. 2e) in equation 2 enables direct determination of λ_a.

Results and Discussion

Table 1 shows the single wavelengths measured with the spectrum analyzer and the resulting artificial wavelength (Eq. 1) in contrast to the wavelength determined directly by the described phase object measurement (Eq. 2). Comparison of the step height measurement of the different artificial wavelengths show that our method works well and produces at least results of the same accuracy as the spectrum analyzer. The result of tactile measurement with a digital micrometer caliper is Δz=0.40 ± 0.01 mm.

Spectrum analyzer Equation (1)			Phase Object Equation (2)	Spectrum analyzer	Phase object direct measurement
λ_1 / nm	λ_2 / nm	λ_a / mm	λ_a / mm	Δz / mm	Δz / mm
783.304	783.389	7.22	7.00	0.40	0.39
783.304	782.991	1.96	1.95	0.41	0.41
783.304	782.780	1.17	1.11	0.43*)	0.41*)

Table 1: Single wavelengths measured with the spectrum analyzer and resulting calculated artificial wavelength (s. Eq. 1) in comparison to the artificial wavelength determined by using the phase object (s. Eq. 2); *)2π ambiguity manually corrected

Finally figure 3 shows exemplarily reconstructed phase maps (a)-(c) and corresponding 3d representations (d)-(f) of the test object. The phase noise (standard deviation) of the phase images is less than $\lambda_a/25$. The flash in (c) and (f) illustrates the necessity of using multiple artificial wavelengths – due to the 2π ambiguousness the step appears smaller than it is.

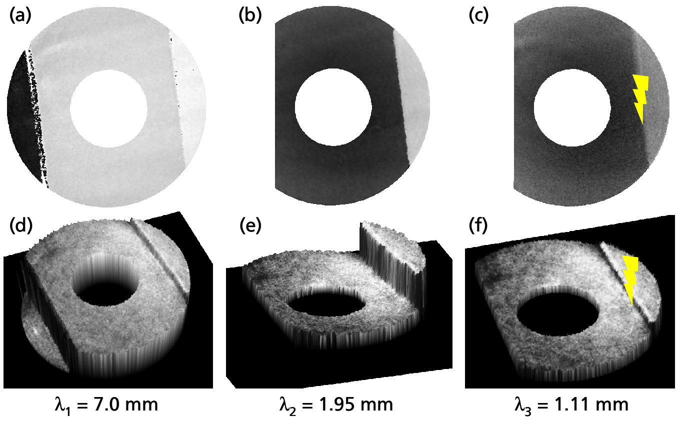

Figure 3: (a)-(c) With different synthetically generated wavelengths (λ_1-λ_3) reconstructed phase of the object wave; (d)-(f) Corresponding 3d representations of the object

In conclusion the presented results show the applicability of the described auto calibration methods for the arbitrary phase steps and the generated artificial wavelengths. As a result the expensive closed-loop piezo controller and spectrum analyzer become redundant which makes the setup more applicable in industrial environments.

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