Dynamic High-Precision ToF Imaging utilizing Single-Shot Synthetic Wavelength Interferometry on Rough Surfaces

Manuel Ballester[1,*], Heming Wang[1,*], Oliver Cossairt[1], Florian Willomitzer[2]
[1] *Department of Computer Science, Northwestern University, Evanston, IL 60208 USA*
[2] *Wyant College of Optical Sciences, University of Arizona, Tucson, AZ 85721*
[*] *Joint first authorship*

mailto: fwillomitzer@arizona.edu

We review our recently developed single-shot multi-wavelength interferometric camera, designed for imaging dynamic objects with rough surfaces [3]. Our imaging system allows for the dynamic reconstruction of macroscopic objects with sub-mm depth precision.

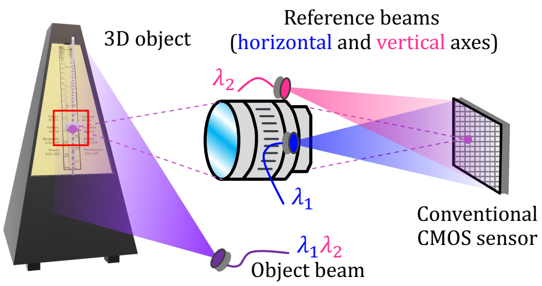

Fig. 1 *Schematic of our single-shot SWI setup.*

3D imaging techniques deliver critical information about an object's topographical properties. Current principles can be roughly categorized into three groups [1, 2]: triangulation-based principles (such as active and passive stereo), reflectance-based principles (such as photometric stereo and deflectometry), and principles based on measuring the optical path length or "Time-of-Flight" (ToF) of light (such as interferometry or so-called "ToF cameras"). ToF-based 3D sensors calculate the light's round-trip travel time from the source to the object and back to obtain the phase map $\phi(x, y)$ of the object surface at each lateral position. The object's depth map is then determined by $z = \lambda\phi/(4\pi)$ [3], where λ represents the respective modulation wavelength (optical wavelength for interferometers, amplitude modulation wavelength for CWAM ToF cameras, etc.). For ToF principles, the depth precision δz is proportional to the used modulation wavelength λ. In conventional amplitude-modulated ToF cameras, the modulation wavelength is limited to several tens of centimeters or even meters due to limitations in silicon manufacturing technology, which in turn limits the achievable precision.

On the other end of the ToF sensor spectrum, interferometric cameras exploit the modulation of the physical wave light field itself. Using optical wavelengths λ with less than a micron, conventional interferometry enables much higher precision. However, imaging optically rough surfaces with conventional interferometers leads to speckle, and the randomized phase map of the speckle field prevents the reconstruction of the surface shape. This problem severely limits the application domain of traditional (single-wavelength) interferometry to smooth object surfaces.

"Synthetic Wavelength Interferometry" (SWI) is a multi-wavelength interferometric technique that emerged a few decades ago for measuring optically rough object surfaces [4, 1]. A classical interferometric setup can be used to obtain the complex speckle field $E(\lambda_1)$ (amplitude and phase) scattered off the rough object surface. The measurement is repeated with a slightly different wavelength to obtain the speckle field $E(\lambda_2)$. Eventually, the synthetic field can be calculated by $E(\Lambda) = E(\lambda_1) \cdot E(\lambda_2)^*$, where * represents the complex conjugate and $\Lambda = \lambda_1\lambda_2/|\lambda_1 - \lambda_2|$ is the synthetic wavelength.

As discussed in [1], Λ is mainly dependent on the difference of the two optical wavelengths, and can be freely selected to be larger than the surface roughness, but still much smaller than the modulation wavelength of conventional ToF cameras. In this case the phase map $\phi(\lambda)$ is not subject to speckle anymore and can be used to calculate the surface shape (we refer to [1, 5, 3] for further details). In [5], the synthetic wavelength approach has even been exploited for "Non-Line-of-Sight" (NLoS) imaging, i.e., imaging hidden objects around corners and through scattering media. However, prior works relied on capturing the two optical fields $E(\lambda_1), E(\lambda_2)$ in a sequential fashion, which makes the measurement of dynamic scenes impossible due to the fast decorrelation of the captured speckle patterns.

In this contribution [3] we present a novel technique and setup that allows to capture the ***entire complex synthetic field in single-shot***, which in turn enables measurements of *dynamic* objects and NLoS scenes (e.g., potential measurements through moving tissue or fog). The schematic of our novel setup is shown in Fig. 1. Our technique

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is inspired by principles known from off-axis interferometry/holography [6]. We illuminate the object surface simultaneously at two different wavelength λ_1, λ_2 (object beam), and directly illuminate the camera chip (conventional CCD/CMOS camera) with two reference beams at λ_1, λ_2, arranged along at two different orthogonal axes. The resulting camera image $I(x, y)$ (Fig. 2a) displays a speckle pattern that is overlayed with crossed fringes. The vertical fringes correspond to the interferences of the λ_1-portion of the object beam with the λ_1-reference beam. Similarly, the horizontal fringes correspond to the interferences of the λ_2-portion of the object beam with the λ_2-reference beam. Interference terms between the fields at λ_1 and λ_2 produce fast-oscillating fringes that are averaged out. Eventually, we retrieve the two complex optical fields $E(\lambda_1), E(\lambda_2)$ from $I(x, y)$ as follows [6, 3]: To retrieve $E(\lambda_1)$, we find the carrier frequency for the vertical fringe direction, shift the Fourier spectrum to set the evaluated carrier frequency as new center frequency, and apply a low pass filter so that only the frequency band around the new center frequency remains. A Fourier back transform eventually delivers the speckle field $E(\lambda_1)$. $E(\lambda_2)$ is retrieved in an analog fashion for the other fringe direction. The synthetic field $E(\Lambda)$ is calculated as described above, and the object surface shape can be recovered from $\phi(\Lambda)$.

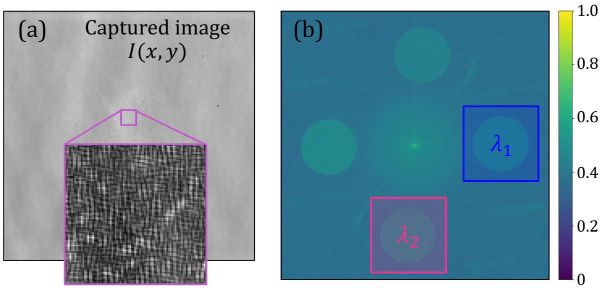

Fig. 2 *(a) Captured camera image. (b) Absolute magnitude of the 2D Fourier transform with frequency bands corresponding to* λ_1, λ_2.

To demonstrate the effectiveness of our novel single-shot technique, we have acquired a "3D video" of an oscillating metronome (see Fig. 3). For this particular measurement, a synthetic wavelength of $\Lambda = 30mm$ was utilized, which leads to a depth precision of $\delta z \approx 4.5mm$ [3]. Figures 3a-3b and 3c-3d show the reconstructed phase maps and 3D models for two selected 3D video frames. The full 3D video can be found here. In [3], we demonstrate further measurements of objects with rough surfaces with a precision up to $\delta z = 330\mu m$. Moreover, we present a first single-shot NLoS measurement through a scatterer. We direct the reader to [3, 1, 5] for more information.

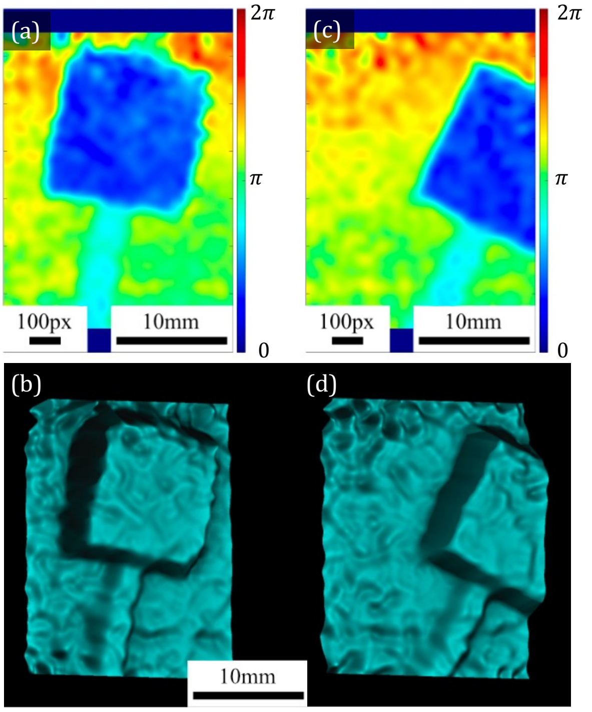

Fig. 3 *Calculated synthetic phase maps (a,c) and 3D models (b,d) for two frames of a 3D video captured with our novel single-shot SWI technique (full video here).*

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