Holographic Measurement of Surface Topography – Limits and New Options

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There is a plethora of options for optical 3D-metrology. Inspired by the progress of digital holography, we discuss two questions: Can we implement *all* classical (non-holographic) sensors via digital holography? And even more interesting: Can digital holography enable options beyond classical sensors?

1 Introduction

Celebrating 60 years of holography, a 600-pages collection [1] displays numerous holographic implementations of optical sensors. In [2] we have shown that virtually all “classical” 3D-sensor principles (triangulation, rough surface interferometry, classical interferometry, slope measuring methods) can indeed be implemented by (digital) holography and that (not much surprising) the ultimate physical limit for the precision and its aperture dependence are essentially the same as for the non-holographic pendants [3]. Reference [4] even demonstrates an option for spatially incoherent sensing with digital holography, to reduce speckle noise.

Here we will discuss if (digital) holography enables 3D-sensors beyond “classical” systems. After digital storage of a complex wave-field, any kind of post-processing can be performed. For radio- and far IR signals post-processing of the phase already allows cm-resolution satellite radar, 1000 km size radio telescopes (LOFAR) and black hole imaging via aperture synthesis. Now we are approaching such options for visible light, which might open a new realm of optical sensors.

2 The path to new options

We restrict ourselves to the most interesting task: to measure the shape *z(x,y)* of daily-life (rough) surfaces. The basic measurement problem for such objects is surface roughness, leading to random-phase speckled signals. Surprisingly, just this behavior opens new options. A close look at the physical limits of *rough-surface interferometry* [3] (white-light interferometry, two-wavelength interferometry) reveals interesting features:

- The ultimate precision limit δz is approximately given by the surface roughness *R*. This limit is much larger than that of classical interferometry, where $\delta z << \lambda$, but -
- the precision limit is *independent from the observation aperture* and the observation distance *z*. That is why satellite radar allows for cm distance precision. (This is fundamentally different from triangulation sensors, where the precision scales with $1/z^2$).

Today, technological progress allows for two-wavelength interferometry in *single-shot* [5]. A synthetic wavelength $\Lambda >> R$ renders the synthetic wavefront scattered from the object virtually smooth (compared to Λ), and speckle-free. And something else: Although the rough object surface generates a smooth synthetic wavefront, the object surface is still scattering light in all directions - we could call it “a rough mirror”. This always ensures that light is scattered into the pupil of the sensor - which, by the way, is not the case if we generate speckle-free reflection via an illumination wavelength $\lambda >> R$.

3 Beyond “classical” sensing

We illustrate the considerations above by the example of looking through scattering media [6]. The method is based on two-wavelength holography. The principle is well known, but as often in science, advances of technology allow for a significant development leap.

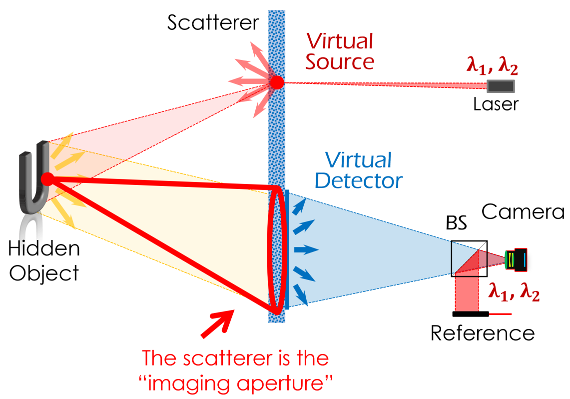

***Fig. 1** Seeing through scattering media. Basic scheme [6]*

The seemingly complicated scheme of Fig. 1 can be easily explained, using the results of sec. 2: The object hidden behind the scatterer is illuminated via the scatterer itself (top), and the same scatterer acts

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as the observation- respectively imaging aperture (bottom).

The synthetic wave emanating from the scatterer can be digitally computed and back propagated to reconstruct the hidden object as shown in Fig. 2.

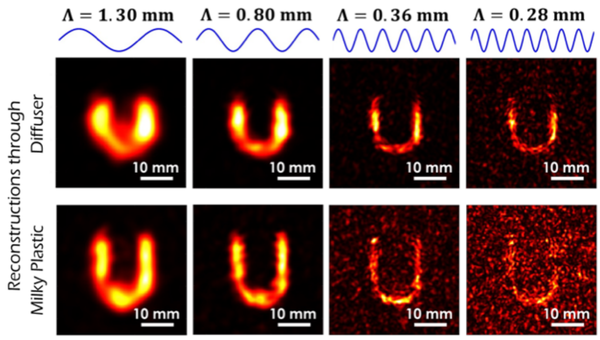

Fig. 2 Seeing through scattering media, results taken from [6]. The lateral resolution is determined by the ratio Λ / numerical aperture; the minimum possible wavelength is limited by the thickness of the scatterer and the transport mean free path.

3 Depth sectioning by multi-Λ holography

For precise 3D-measurements via depth slicing, white-light interferometry is scanning the (≈1μm-) short temporal coherence function along the z-axis. A short (but periodic) coherence function can be generated as well by a frequency comb. In [6,7], this principle is exploited by generating a synthetical "*frequency comb"* from 59 synthetical wavelengths Λ. For the results shown in Fig. 3, 59 captured complex optical fields are computationally superimposed to mimic pulse interferometry. By changing amplitude and phase of each optical field, the pulse can be freely manipulated in the computer, after the measurement.

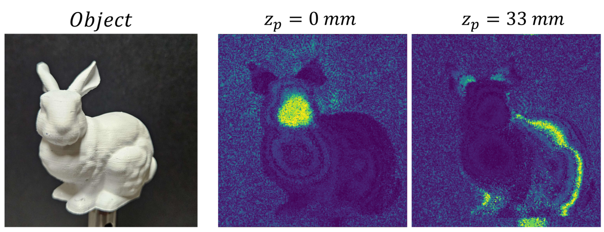

Fig. 3 *Depth slicing by synthetic pulse interferometry. 59 synthetical wavelengths Λ generate a synthetic pulse that can be used to section the object at different depths z_p.*

4 Self-luminous objects

The novel technologies to digitally store the phase of an optical signal, fast and with large space-bandwidth, justifies some enthusiasm. Certainly, there will be many new sensors and applications not invented yet. However, there is a big gap: So far, we need coherent illumination. What about self- luminous objects like stars? Phase acquisition via Long Baseline (star) Interferometry (LBI) is possible up to a few hundred meters. However, "visual astronomy" is enviously looking at the Event Horizon Telescope (EHT) project: Via aperture synthesis from 8 radio telescopes located around the earth, an angular resolution of 20 μarcsec was achieved to image the shadow of the black hole at the center of M87 galaxy [8]. This example of Very Long Baseline Interferometry (VLBI) used a long wavelength of 1.3mm, and ultra-precise time stamps via local atomic clocks were necessary.

In ref [9] the reader will find an enlightening discussion of fundamental difficulties - prominent is the small number of photons - and prospects for a future long baseline interferometry in the visible range.

6 Conclusion

Fast digital storage of phase and amplitude offers a) options to re-implement so far non-holographic sensors and b) new sensors for applications not possible until now. Capturing complex signals of self-luminous objects such as stars will become the scientific adventure of the future.

References

[1] W. Osten, R. Kowarschik, Y. Bai (eds.), *Light: Advanced Manufacturing* (2022)3, https://www.light-am.com

[2] G. Häusler, F. Willomitzer: „Reflections about the holographic and non-holographic acquisition of surface topography: where are the limits", in: *Light: Advanced Manufacturing* (2022)3:25, 226-235

[3] G. Häusler, S. Ettl, "Limitations of optical 3D-sensors", in: *Optical Measurement of Surface Topography,* Richard Leach (Ed.), Springer Verlag Berlin Heidelberg 2011, pp. 23-48

[4] C. Falldorf, S. Huferath-von Luepke, C. von Kopylow, R. B. Bergmann, "Reduction of speckle noise in multiwavelength contouring", *Appl. Opt.* 51 (2012) 8211-8215

[5] M. Ballester, H. Wang, J. Li, O. Cossairt, F. Willomitzer; "Single-shot ToF sensing with sub-mm precision using conventional CMOS sensors". *ArXiv Preprint* arXiv:2212.00928, 2022

[6] F. Willomitzer, P. Rangarajan, F. Li, M. Balaji, M. Christensen, O. Cossairt; "Fast Non-Line-of-Sight Imaging with High-Resolution and Wide Field of View using Synthetic Wavelength Holography", *Nature Communications* 12, 6647 (2021)

[7] P. Cornwall, M. Ballester, H. Wang, F. Willomitzer; „Towards synthetic light-in-flight", *Computational Optical Sensing and Imaging (COSI)*, 2023

[8] Event Horizon Collaboration et al 2019, *Astrophysics J. Lett.* 875, L1

[9] J. Bland-Hawthorne, M. J. Sellars, J. G. Bartholomew, "Quantum memories and the double-slit experiment: implications for astronomical interferometry", *arXiv:*2103.07590v1, 13 Mar 2021

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