Referenceless phase holography for displaying 3D scenes captured by digital holography

André F. Müller*, Beñat Gutiérrez-Cañas Pazos*, Claas Falldorf*, Ralf B. Bergmann*,**

*BIAS - Bremer Institut für angewandte Strahltechnik GmbH, Klagenfurter Str. 2, 28359 Bremen, Germany
**University of Bremen, Faculty of Physics and Electrical Engineering, 28359 Bremen, Germany

mailto:amueller@bias.de

Referenceless phase holography (RELPH) displays full wave fields (amplitude and phase) of arbitrary 3D scenes through the interference of two phase-modulated wave fields of constant amplitude. Aimed at quasi-real-time holographic video transmission, we present the 3D-display of holographically captured scenes with RELPH, transforming the recorded hologram for consistent optical reconstruction.

1 Introduction

Many widespread commercial realizations of 3D-displays depend on stereoscopy, i.e. processed 2D-images addressing the two eyes individually. This generally causes a vergence-accomodation conflict due to a mismatch between the distance of a virtual 3D object and the focusing distance. This can be circumvented by holographic displays, which reconstruct the entire wave field and satisfy all depth cues of the human perception, including full parallax, a large depth of field, and a wide angle of view. To display real, physically existent 3D-scenes holographically, the wave fields of 3D-scenes are first captured via digital holography [1].

One of the primary problems for the dynamical optical reconstruction of digital holograms is the low space–bandwidth product (SBP) of currently available spatial light modulators (SLM). A novel method that aims at the efficient use of the SBP is the referenceless phase holography (RELPH) [2, 3]. Instead of recreating the holographically recorded interference pattern, as obtained from the superposition of an object wave with a reference wave, it makes use of multiple phase-only SLMs to generate a desired complex amplitude at a given plane in space.

2 Mathematical description and RELPH-setup

For the display of an arbitrary optical wave field $E(x, y)$ with intensity distribution $I(x, y)$ and phase distribution $\phi(x, y)$, RELPH decomposes the wave field into two mutually coherent wave fields,

$$E(x,y) = \sqrt{I(x,y)}\exp[i\phi(x,y)] \quad (1)$$
$$= E_1(x,y) + E_2(x,y), \quad (2)$$

where $E_1(x, y)$ and $E_2(x, y)$ are pure phase fields of constant amplitude,

$$\begin{aligned} E_1(x,y) &= \exp\left[i\phi_1(x,y)\right] \\ E_2(x,y) &= \exp\left[i\phi_2(x,y)\right]. \end{aligned} \quad (3)$$

The phase distributions ϕ_1, ϕ_2 are given by

$$\begin{aligned} \phi_1(x,y) &= \phi(x,y) + \arctan\left(\frac{\sqrt{4-I(x,y)}}{\sqrt{I(x,y)}}\right) \\ \phi_2(x,y) &= \phi(x,y) - \arctan\left(\frac{\sqrt{4-I(x,y)}}{\sqrt{I(x,y)}}\right), \end{aligned} \quad (4)$$

where without restriction of generality intensity and phase are limited to

$$I(x,y) \in [0,4] \quad \text{and} \quad \phi(x,y) \in [0,2\pi]. \quad (5)$$

The resulting interference field of the superposition reconstructs any given wave field $E(x, y)$ [2] in line with eq. (2).

For the experimental realization, the phase-modulation of the wave fields $E_1(x, y)$ and $E_2(x, y)$ is carried out by two phase-only SLMs of a liquid crystal on silicon (LCOS) type in a Michelson-interferometer-based setup. Using a laser with a wavelength of 633 nm as a light source, the light is collimated and linearly polarized towards the slow birefringent axis of the SLMs. As shown in the depiction of the experimental setup for RELPH in Fig. 1, the SLMs are placed in the two interferometer arms of a Michelson-interferometer. After being modulated by the SLMs the mutually coherent wave fields are brought into superposition by the beam splitter. The superposed wave fields then reconstruct 3D scenes in image planes anywhere in front or behind the SLM plane.

Since the wave field results from the superposition of two separate phase-fields the precise mutual alignment of these phase-fields and consequently of the SLM is essential to avoid spurious interference patterns in the reconstruction. In addition, mechanical or thermal deformations result in phase differences between the wave fields degrading the image quality. These deformations can however be compensated by measuring the phase difference through phase shifting via the SLMs and subtracting the resulting phase difference from one SLM [2].

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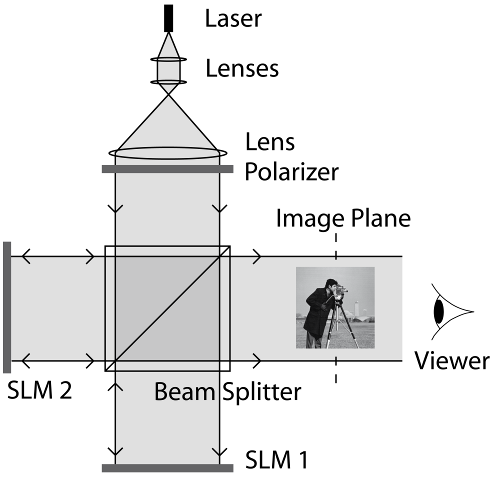

Fig. 1 *Experimental setup for generating referenceless phase holograms. Two spatial light modulators (SLMs) placed in the interferometer arms of a Michelson-interferometer modulate mutually coherent wave fields to reconstruct arbitrary 3D scenes.*

3 Holographic reconstruction of real 3D scenes

For the demonstration of a holographic reconstruction of physically existent 3D scenes, two toy building blocks were captured via phase-shifting holography. The wave field, computationally reconstructed from the complex hologram of the toy building blocks, is then propagated by the angular spectrum method into the SLM plane. From this the RELPH diffraction patterns are calculated according to eq. (4).

There usually exists a mismatch between the pixel pitch of the camera recording the original hologram and the pixel pitch of the SLMs modulating the reconstruction via RELPH. While in the lateral dimensions of the reconstruction this pixel pitch mismatch only results in a scaling of the reconstructed scene, in the direction of propagation it results in distorted depth information. To overcome this issue, the pixel pitch of the computationally reconstructed wave field is transformed via sinc-interpolation. For this purpose, the wave field is transformed in the Fourier-space, where it is cut to the required size for the Fourier-components to match the spatial frequencies corresponding to the SLM's pixel pitch. The retransformed sinc-interpolated wave field is then propagated into the SLM plane where diffraction patterns for the RELPH reconstruction are calculated as described above.

The sinc-interpolation may introduce additional degradations due to the interpolation of speckle noise. In the case of the measured wave field having a higher space-bandwidth-product than the reconstructing SLMs, these additional speckle degradations can be reduced by temporal multiplexing of different sinc-interpolated wave fields with varying speckle-noise. Choosing slightly different areas of identical size in Fourier-space results in changed phase distributions and consequently changed speckle distributions for each reconstruction.

The RELPH reconstruction of the holographically captured toy building blocks shown in Fig. 2 was displayed in a distance of 200 mm in front of the SLM plane with a CCD camera. Fig. 2(a) shows a reconstruction with high speckle noise, whereas in Fig. 2(b) 20 different intensity distributions were temporally averaged resulting in a significant reduction in speckle noise to the level of the initial wave field.

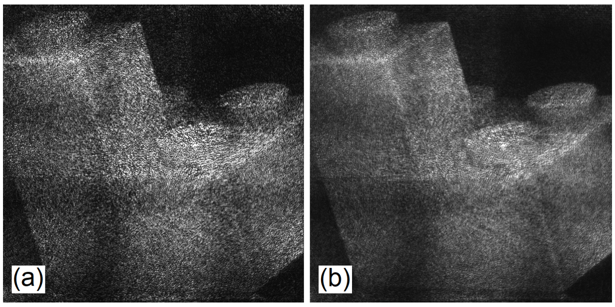

Fig. 2 *3D-display of a toy building block with RELPH after the transformation to the pixel pitch of the SLMs. (a) Reconstruction with high speckle noise. (b) Temporally averaged intensity distributions of varying speckle patterns resulting in lower speckle noise.*

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References

[1] P. W. M. Tsang and T.-C. Poon, "Review on the state-of-the-art technologies for acquisition and display of digital holograms," IEEE Transactions on Industrial Informatics **12**(3), 886–901 (2016).

[2] T. Kreis, "3-d display by referenceless phase holography," IEEE Transactions on Industrial Informatics **12**(2), 685–693 (2016).

[3] A. F. Müller, I. Rukin, C. Falldorf, and R. B. Bergmann, "Multicolor Holographic Display of 3D Scenes Using Referenceless Phase Holography (RELPH)," Photonics **8**(7), 247 (2021).