Advantages of Phase Modulating MEMS for Full 3D Hologram Scene Reconstruction

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Abstract: Phase LCOS are established for hologram reconstruction but also have drawbacks. MEMS can have superior modulation quality. An analysis of modulation errors and their impact on hologram reconstruction for full 3d holographic scenes is demonstrated. © 2022 The Authors

1. Main Text

1.1. Introduction

Phase-only liquid-crystal-on-silicon (LCOS) micro-displays are most common for holographic use cases, such as head-mounted and head-up displays (HMD, HUD). Although representing the most prevalent technology employed in digital holography, those devices suffer from several effects, such as phase flicker in digital backplane systems, limited LC-switching speed, and fringe-field effects whose impact drastically increases with decreasing pixel sizes [1]. While some of these effects can be compensated to some extent by calibration techniques and encoding algorithms, others constitute general limitations of the device performance.

Recent studies promote artificial intelligence-driven methods and phase-regularization procedures to account for such imperfections and to improve the image quality of in-focus holographic reconstructions [2, 3]. These approaches lead to a smooth phase distribution in the hologram plane inducing reduced speckle artifacts which can be attributed to the correlation of interacting object-point phases [2]. More importantly, low-frequency and flat phase modulations also reduce the impact of fringe-field effects [1]. However, smooth variations of object-point phases also lead to a small eyebox and significantly reduced depth cues, such as defocus blur and motion parallax [4], and advanced concepts are required to allow for high-quality, true 3D, and realistic holography.

Phase-modulating microelectromechanical systems (MEMS) provide several advantages and a promising alternative to LCOS displays. They have been described by Texas Instruments in recent publications demonstrating their potential with respect to holographic applications. In contrast to LC devices, the fringe-field effect is not present in these systems and they allow for smaller pixel sizes without substantial interaction between adjacent mirrors. MEMS structures are also capable of very high switching speeds up to several kilohertz [5]. However, currently available prototypes are still limited with respect to bit depth and étendue.

This work focuses on optical simulations modeling characteristic aspects of MEMS structures and typical imperfections connected to these systems and their impact on the image quality of holographic reconstructions. These results contribute to REALHOLO developing MEMS displays with a small pixel size of 6 x 4 μm^2, a high pixel count of 9.6 MP, and 8-bit phase modulation [6].

1.2. Bit depth

One of the most important parameters of a phase-only spatial light modulators (SLMs) is the number of phase levels each pixel can address. To investigate the influence of this attribute on the image quality of a holographic scene, a typical HUD scene is encoded in a complex hologram as described in [7]. Phase-only holograms are calculated using an iterative approach based on the Gerchberg-Saxton algorithm. Eventually, the optical field is numerically reconstructed and the image quality is determined by the intensity contrast (normalized to the maximum value at 8 bit), the peak-signal-to-noise ratio (PSNR), and the structural similarity (SSIM). In accordance to other publications (e.g. [5]), major improvements cannot be noticed above 4 bits when only PSNR or SSIM are considered. However, considering the intensity contrast, which is a critical parameter in HMD and HUD applications [8], a significant progress can be observed in the range above 4 bits, especially in the case of Fresnel holograms.

This is the author's version of this paper. See also:
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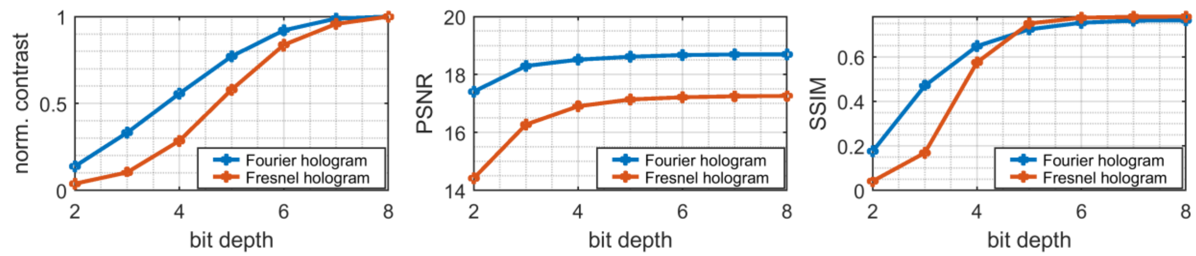

Fig. 1. Bit-depth-dependent quality metrics of simulated reconstructions of 3D scenes from phase-only holograms.

1.3. Mirror imperfections

Although not being prone to fringe-field effects, other imperfections can limit the performance of MEMS devices. For example, different responses of individual mirrors to the applied voltage can be induced by variations of the mechanical properties of individual actuators, electrical crosstalk between adjacent mirrors, or leakage effects. Fig. 2 (a) exemplarily shows the normalized intensity contrast of a reconstructed HUD scene as function of the maximum value of a random distribution of phase-stroke errors and the inverse spatial frequency of the error variation over the display plane. As can be seen from these results, the image quality is more affected by phase stroke errors in situations, where their sources affect pixels more independently. At least 99% of the optimal contrast is preserved if the maximum error is kept below the phase resolution of the 8-bit device. In addition, structural imperfections and unoptimized design parameters can lead to tilted or warped mirror planes. As can be seen from the simulation results in Fig. 2 (b) and (c), the contrast of the holographic reconstruction in the phase-only configuration is almost preserved below a tilt angle of 0.1° and an average warp lower than 100 nm with a FWHM of the stochastic distribution below 20 nm.

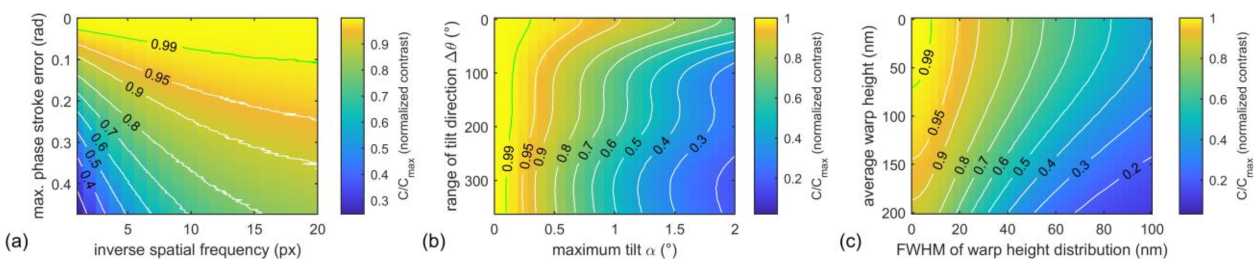

Fig. 2. Normalized intensity contrast of a simulated reconstruction of a 3D scene for three characteristic types of mirror errors is shown for randomly distributed (a) phase stroke error, (b) tilted mirror planes, and (c) mirror warp.

In conclusion, this work contributes to design standards and device tolerances for the development of advanced MEMS technology by the REALHOLO consortium. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101014977. It is an initiative of the Photonics Public Private Partnership. We like to thank all partners of the consortium, especially Peter Dürr from Fraunhofer IPMS for the valuable discussions.

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