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Printing of digital holographic content as a color white light viewable silver-halide hologram

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The most advanced 3D imaging technology of digital holography is holographic printing. It combines digital and analogue holography by recording a hologram onto a holographic silver-halide emulsion as a volume reflection hologram from digital contents fed to a spatial light modulator. The hologram is built as a 2D array of successively recorded elemental analogue holograms. In the first developed holographic printing technique multiple perspectives of the 3D scene are incoherently captured and printed as a holographic stereogram to allow the viewer to perceive 3D objects by binocular vision. Recording of only directional data leads to distorted reconstruction from the recorded stereogram. Direct printing of holographic fringes as a thin transmission hologram onto a holographic emulsion without a reference wave provides non-distorted reconstruction but without color selectivity. The paper presents a color holographic wavefront printer which prints a white light viewable hologram on a silver-halide emulsion as a two-dimensional array of elemental holograms. The 3D contents for the printer are formed as a set of computer generated holograms and contain depth, directional and colour information. The input data for each elemental hologram are fed to an amplitude spatial light modulator. The light wavefront coming from a three-dimensional object is extracted by a spatial filter and demagnified before recording. The printed hologram provides highly photorealistic reconstruction similar to an analogue reflection hologram.

Keywords: Holography, holographic printer, 3D imaging, silver-halide emulsion, computer generated holograms.

INTRODUCTION

The most advanced 3D imaging technology of digital holography is holographic printing [1]. It combines digital and analogue holography by recording a hologram onto a holographic emulsion from digital contents fed to a spatial light modulator (SLM). The hologram is built as a 2D array of successively recorded elemental analogue holograms. The first developed printing technique was the holographic stereogram printing [2,3]. In this printer multiple perspectives of the 3D scene are incoherently captured and processed to allow the viewer to perceive 3D objects by binocular vision. These data are recorded as a volume reflection hologram on a silver-halide emulsion. Recording of only directional data leads to distorted reconstruction from the recorded stereogram. Non-distorted 3D reconstruction is provided by a direct fringe printer which records a thin transmission computer generated hologram (CGH) onto a holographic emulsion without a reference wave [4], and the printed hologram has no color selectivity. The drawbacks of these two printers are avoided by the wavefront printing proposed independently by us [5] and Yoshikawa [6]. In this approach, the SLM displays a CGH which diffracts light to be recorded as a volume reflection hologram. The paper presents design and implementation of a color holographic wavefront printer with demagnification of the object beam which makes possible mosaic delivery of primary colors on a silver-halide emulsion.

GENERATION OF 3D CONTENTS AND OBJECT BEAM EXTRACTION

The essence of the wavefront printing is optical extraction of the light wavefront which carries information about the 3D object from the light diffracted by a SLM which displays a CGH of this object. We proposed a printer, in which the CGHs for the elemental holograms were displayed in succession on amplitude SLM. The CGH

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synthesized for this SLM is a 2D real-valued array which encodes four terms:

$$H(\xi,\eta) = O(\xi,\eta)O^*(\xi,\eta) + R(\xi,\eta)R^*(\xi,\eta) + O(\xi,\eta)R^*(\xi,\eta) + R(\xi,\eta)O^*(\xi,\eta) \quad (1)$$

where $O(\xi,\eta) = a_O(\xi,\eta)\exp[i\varphi_O(\xi,\eta)]$ and $R(\xi,\eta) = a_R(\xi,\eta)\exp[i\varphi_R(\xi,\eta)]$ are the complex amplitudes or wavefronts of mutually coherent object and reference beams that digitally interfere in the plane (ξ,η) of the CGH or the SLM respectively; $a_{O,R}(\xi,\eta)$ and $\varphi_{O,R}(\xi,\eta)$ are the amplitude and phases of these wavefronts and "i" is the imaginary unit. The sum of the first two terms forms the zero-order term while the other two terms give the beam coming from the object and the beam converging to the object. In the proposed printing system, the beams encoded in the CGH and diffracted from the SLM focused at separate spots in the back focal plane of a lens which collected the beam diffracted from the SLM when the CGH was calculated in off-axis geometry. Thus the object wavefront was optically extracted by spatial filtering in this plane. The extracted object beam was further demagnified to be recorded onto the holographic silver-halide emulsion as a small size elemental hologram. In view that the object beam corresponded to the light beam scattered from the 3D object, we called our printer a wavefront printer.

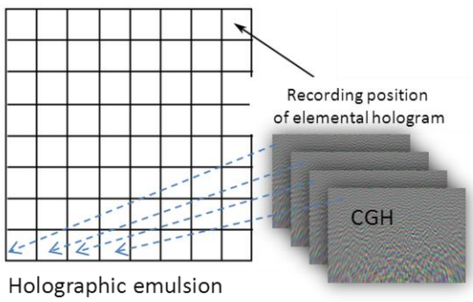

Fig. 1. Printing a volume reflection hologram as a collection of elemental holograms recorded from a set of CGHs.

The hologram printed by the wavefront printer was built as a 2D collection of elemental holograms which are recorded in succession. The 3D contents to be printed consisted of a set of CGHs. Each CGH was calculated according to the position of a given elemental hologram (Fig. 1). The elemental hologram in the wavefront printer is a part of the whole hologram and exhibits all properties of a hologram by encoding color, directional and distance related phase information. Theoretically, its size is limited by the used active area of the SLM. Substantial decrease of the elemental hologram in our printer design made possible mosaic delivery of exposures at primary colors when each elemental hologram got a single color [7]. Separation of color channels allowed for avoiding the crosstalk and for achieving high diffraction efficiency.

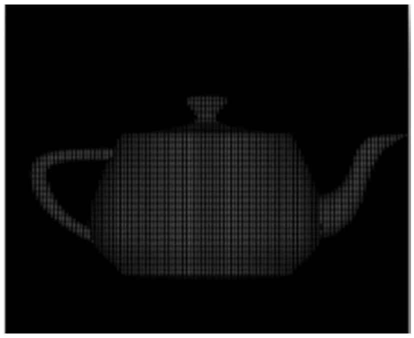

Fig. 2. Point-cloud representation of a 3D object.

We adopted the ray-casting approach to generate the 3D contents by using a point-cloud object representation (Fig. 2). The point cloud method considers the 3D object as a collection of point light sources which emit spherical waves. A set of point clouds with P self-emitting points each was extracted for all elemental holograms. The fringe pattern for a given elemental hologram was computed using the corresponding point cloud. For the purpose, we developed content creation software with tools for forming point-clouds of 3D objects and computing of CGHs at RGB wavelengths. Usage of high resolution SLM for displaying CGHs makes computation of 3D contents a complicated task at the chosen small size of the elemental hologram. To accelerate computation we developed a fast phase-added stereogram algorithm [8] that allowed for fast Fourier transform (FFT) implementation. The principle of fast CGH computation is elucidated in Fig. 3. The point "p" in a point cloud with spatial coordinates (x_p, y_p, z_p) is located at the distance $r_p = \left[(\xi - x_p)^2 + (\eta - y_p)^2 + z_p^2\right]^{1/2}$ from the point (ξ,η) on the hologram plane located at $z = 0$. This point emits three spherical waves at the RGB wavelengths with different amplitudes and initial phases (a_p, ϕ_p). The algorithm partitioned each CGH into $M \times N$ square segments. The segment size is chosen small enough to use a plane wave for description of contribution of a point to the fringe pattern on the segment. The spatial frequencies (u_{mn}^p, v_{mn}^p) of the sinusoidal function for the point "p" and the segment $(m,n), m = 1..M, n = 1..N$ at a given wavelength are determined with respect to the segment central point. The distance between the point "*p*" and the central point is r_{mn}^{p} . The initial phase of the sinusoid, Φ_{mn}^{p} , is a crucial parameter for matching the wavefronts of the plane waves diffracted from all segments. The phase Φ_{mn}^{p} contains the phase ϕ_p of the wave coming from the point "*p*" and may include the distance related phase. It is also determined with respect to the central point. Taking in view all object points, the fringe pattern across the segment is approximated as a superposition of 2D complex sinusoids. The fringe pattern in each segment was calculated by FFT of the 2D distribution in the spatial frequency domain of complex amplitudes associated with the points in the point-cloud seen from this CGH. Locations of the complex amplitudes corresponded to spatial frequencies determined with respect to the center of the segment. The segment size should be small to ensure good reconstruction from the phase-added approximation. That's why we applied the FFT with zero-padding for a number of pixels larger than the number of pixels in the segment to decrease the error due to discretization of the spatial frequencies. We used CUDA platform for parallel programming and computing to implement the developed algorithm.

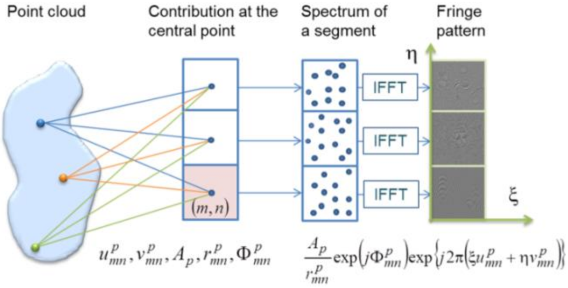

Fig. 3. Schematic of the accelerated computation of fringe patterns for elemental holograms.

RESULTS

The wavefront printer we built is depicted in Fig. 4. Three continuous wave DPSS lasers emitting at 640 nm, 532 nm and 473 nm were used. Each laser exposed a single elemental hologram. The first polarizing beam splitter (PBS_1) after the collimating system formed the object and reference beams. The object beam illuminated the amplitude type SLM by means of the PBS_2. We used a liquid crystal on silicon projector Sony VPL-HW10 SXRD with 1920×1080 pixels and a pixel interval 7 µm. After diffraction from the SLM, optical filtering and demagnification by the telecentric lens system, the beam impinged the holographic silver-halide plate. Due to demagnification, the pixel interval at the plane of the hologram was 0.42 µm. We used the silver-halide emulsion Ultimate08 with an average grain size of 8 nm. The plate was moved by a X-Y stage at precision of 1 µm. For uniform intensity distribution at the object beam footprint on the hologram, we used only the central part of the SLM, so the size of the elemental hologram was 380 µm by 380 µm. The shutters controlled the exposure time. A personal computer controlled the wavefront printer operation.

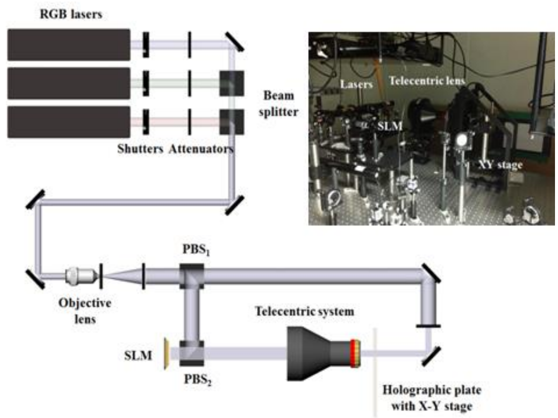

Fig. 4. Optical scheme and photograph of the wavefront printer with demagnification of the object beam.

Fig. 5. Photographs of reconstruction from printed holograms.

We achieved bright 3D reconstruction with a motion parallax at saturated colors from holograms of test objects (Fig. 5). The size of the holograms in the top row and the left hologram in the bottom row is 5 cm by 5 cm. They are built from 131×131 elemental holograms. Thus we proved feasibility of recording analogue color volume holograms from digital contents by applying spatially separated exposures at primary colors to the elemental holograms. The SLM partitioning was applied for enhancement of reconstruction quality at mosaic delivery of exposures for primary colors. We checked a 3 × 3 partitioning scheme which results in an elemental hologram built as a mosaic of 9 non-overlapping color patches recorded at the RGB wavelengths. Thus we achieved smooth color reproduction without high-end optical components. The reconstruction from a 9 cm by 9 cm hologram of a bunch of flowers that has been printed by this method shows very good quality (Fig. 5). The reconstructions prove that the wavefront printer is a desirable choice for realistic 3D imaging with quality of reconstruction as in analogue holography.

CONCLUSION

In summary, we described a holographic printer for analogue reflection holograms from digital contents. The information about a color 3D object is encoded in a set of computer generated holograms which are printed as a set of color elemental holograms on a silver-halide emulsion. The printed hologram is a full parallax hologram and provides realistic 3D imaging. For accelerated generation of 3D contents for the numerous elemental holograms, a fast phase-added stereogram approach is proposed. High quality of reconstruction from the printed white-light viewable holograms recorded from the computer generated holograms produced with accelerated computation proved the algorithm efficiency.

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ПРИНТИРАНЕ НА ЦИФРОВИ ХОЛОГРАФСКИ ДАННИ КАТО ЦВЕТНА ОТРАЖАТЕЛНА ХОЛОГРАМА ВЪРХУ СРЕБЪРНО-ХАЛОГЕНИДНА ЕМУЛСИЯ

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(Резюме)

Най-напредналата технология за триизмерно визуализиране с цифрова холография е холографският принтер. Той обединява цифровата и аналогова холография чрез запис на отражателна холограма върху сребърно-халогенидна емулсия от цифрови данни, подавани към пространствено-светлинен модулатор. Холограмата е масив от последователно записвани елементарни аналогови холограми. Първият разработен холографски принтер се базира върху некохерентен запис на изображения на тримерната сцена от различни ъгли и принтиране на стереограма, които се възприема тримерно посредством бинокулярно зрение. Записът само на посоката и цветовете изкривява възстановенич образ. Директното принтиране на интерференчни ивици като тънка пропускаща холограма върху холографска емулсия без опорен сноп дава неизкривено възстановяване без селективност към цветовете. В статията се представя цветен холографски принтер на вълновия фронт, който принтира възстановявана с бяла светлина холограма като двумерен масив от елементарни холограми върху сребърно-халогенидна емулсия. Тримерните данни за този принтер се формират като съвкупност от компютърно генерирани холограми и съдържат информаци за дълбочината, посоката и цвета. Данните за всяка елементарна холограма се подават на амплитуден пространствено-светлинен модулатор. Вълновичт фронт от тримерния обект се извлича с пространствен филтър и се намалява напречно преди записа. Принтираната холограма предоставя реалистично възстановяване подобно на това от аналогова отражателна холограма.