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Holographic stereogram printing based on digitally computed content generation platform

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ABSTRACT

In this paper, we have implemented a 3D content generation simulator based on integration of phase-only spatial light modulator (SLM) and LabVIEW software to develop a holographic stereogram printer that consists of a coherent laser, a spatial light modulator and X-Y translation stage with stepper motors. This content generation platform provides encoding of directional information extracted from rendered perspective images of real or virtual 3D object. There are mainly three parts related to the implementation for holographic stereogram printer. In the first part, "Digital content generation" phase-only SLM will be applied to the holographic printer system by loading series of perspective 2D images for each holographic elements (hogel). Regarding this part, phase-only SLM can be converted into an amplitude modulator by adjusting the angles of the polarizer. The second part is "Control system" made in LabVIEW based platform for automatic recording of the holographic stereograms which is synthesized from previous part. The third implementation part is "Optical system" for printing of parallax-related hogels on the holographic plate. To check the performance of the developed approach, numerical simulations and optical experiments are implemented. The hogel images are sequentially exposed using the perspective images to form the whole holographic stereogram on the holographic light sensitive material.

Keywords: Computer-generated hologram (CGH), holographic printer, holographic stereogram, three-dimensional (3D) display.

1. INTRODUCTION

Holographic stereogram combines the recording principle of digital holography and stereoscopic technique to provide binocular parallax phenomena. Its printing process is based on a holographic recording of 2D images with different parallax information of a 3D object. There have been conducted many holographic printers, which can be classified into three main categories: 1) holographic stereogram printer; 2) holographic fringe printer for CGH; 3) wave-front printer. A common feature of all holographic printers is division of the printed hologram into a 2D array of elemental holograms. Information to be recorded in an elemental hologram is displayed on a spatial light modulator (SLM). Holographic printer records the information provided by SLM onto the light sensitive holographic material by the way analog hologram is recorded. The holographic stereogram printers can be used only for the holographic stereogram, which is synthesized from an array of two-dimensional (2D) perspective images. The holographic stereograms can be divided into horizontal parallax only (HPO) stereograms and full parallax stereograms. The holographic stereogram and wave front printers are proposed for animated 3D visualization through space shifting of multiple holographic elements (hogels) which improve the space bandwidth (SBP) and depth performance of the system. Keehoon Hoog, Jiyung Park [1, 2] et.al created a printing system of holographic stereogram based on holographic element (hogel) and enhanced the resolution of holographic stereogram using hogel overlapping method.

The holographic fringe printers print the fringe pattern of 3D scene and can be used for many kind of holograms including Fresnel, cylindrical, holographic stereogram and rainbow hologram so on. The fringe printing is directly imprinted the fringe pattern on light sensitive material. Matsushima [3] et.al developed a fringe printer consists of a laser and X-Y stage with stepper motors. Prof. Hiroshi Yoshikawa's [4] group developed direct fringe printer for computer-generated holograms. There is an another type of printer that records wave front generated by spatial light modulators (SLM) and can produce volume holograms [6,7]. The holographic wave front printer decodes the 3D object wave front from the CGH and records it as an analog volume hologram. The holographic stereograms can be recorded as volume holograms that reconstructs 3D images under white light illumination. The fringe pattern produced by interference of the generated wave

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front by the reference wave is recorded on the holographic material as a volume hologram. A fast holographic fringe pattern generation algorithm is required for the wave front printing. The SLM in wave front printer generates the wave front of numerically synthetic object fields. The algorithms for CGH computation can get directional, color and depth information from a 3D object or scene. Generating the printed hologram as a 2-D array of elemental holograms is similar to the ray casting approach which can be applied for CGH computation. Due to the SLM size, the hologram plane is partitioned into a set of elemental holograms. The ray casting approach is commonly used to build a point cloud object representation from each sub holograms [8-10].

In this paper, we have developed a holographic stereogram printer that consists of a coherent laser, a spatial light modulator (SLM) and X-Y translation stage with stepper motors. The printing system can be divided into three parts; 1) 3D content generation for holographic stereogram printer; 2) control system for automatic recording; and 3) implementation of optical system. The control system consists of a personal computer with an X-Y stage with stepper motor, SLM display and an electrical shutter control. The LabVIEW based application controls the stepper motors of X-Y translation stage, SLM loading image and mechanical shutter at the same time. After recording first hogel image, X-Y stage is translated horizontally and vertically for the next hogel recording. This process is repeated for all hogel images until the entire hologram is exposed on the holographic material. The principle of the full parallax holographic stereogram printing technique is schematically illustrated in Fig 1.

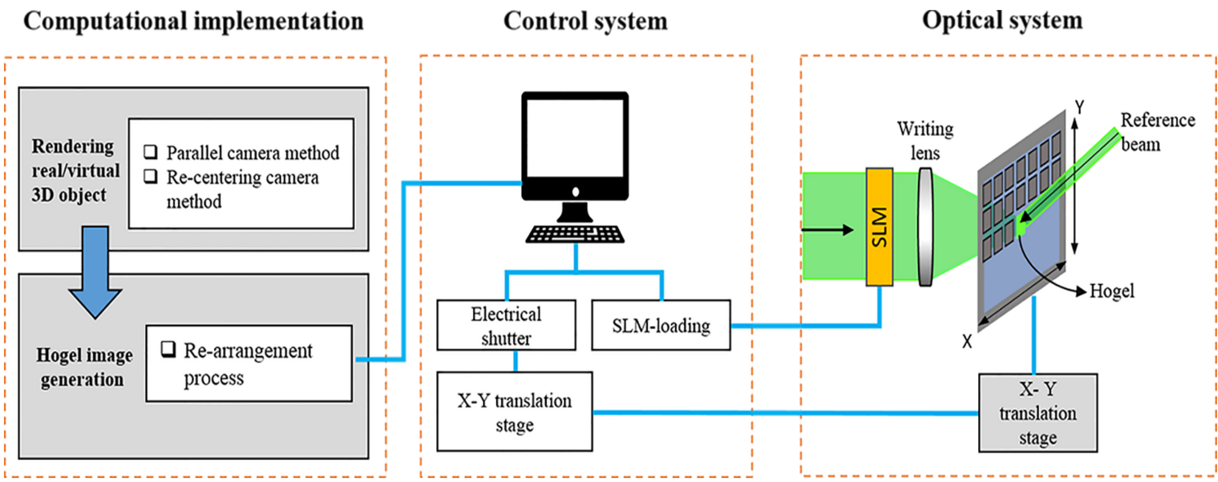

Figure 1. Schematic configuration of a holographic stereogram and printing process of a parallax-related images.

2. HOLOGRAPHIC STEREOGRAM PRINCIPLE

2.1 Acquisition of perspective images and hogel image generation

Holographic stereogram is a combination of digital holography and binocular stereo vision technique. It has several advantages compared with a conventional holographic display, which makes it the most promising technique for 3D displays. A holographic stereogram encodes an array of two-dimensional (2D) parallax-related images which are generated from series of perspective images. The printing process consists of the following main steps: 1) acquisition of the perspective images; 2) post-processing of the acquired images to transform parallax-related images for distortion free reconstruction; 3) holographic recording of the elemental holograms. Acquisition of the perspective images needs a simple camera using different rendering techniques in computer graphic modeling software. The perspective images can be captured from a 3D computer graphic model or from a real object captured from different angles. We used Blender software to render perspective images of 3D scene. A single camera is used to capture a directional information taken from a real or virtual object and the camera is moved on the plane parallel to the holographic stereogram plane. The rendered camera field of view (FOV) and writing lens FOV are adjusted to be an equal size. To view distortion-free reconstruction far from the hologram, perspective images need to be transformed to form the separate parallax images corresponding to different hogel images in the hologram plane. Both perspective and hogel images are two-dimensional arrays but in different dimensions. The holographic stereogram plane is located at $x - y$ plane and composed from two-dimensional parallax related or hogel image. Directional information obtained from the perspective images is rearranged to generate hogel images or separate parallax images. These parallax-related images, composed from different perspective images are displayed on phase-only SLM and recorded onto a holographic plate as elemental hologram. The resolution of perspective images is defined by the SLM resolution. The SLM can be transparent or reflective liquid crystal display (LCD). Transformation process of perspective images to the parallax-related images is presented in Fig 2. The parallax-related images are captured by virtual camera and generated by a plane wave with a certain direction, which is diffracted by the hogel (i, j) on the holographic stereogram plane. Similarly, the pixel (i, j) of every hogel image is diffracted by the hogel (i, j), which corresponds to the different locations in the holographic stereogram. Re-arrangement process is made to generate hogel images H_{ij} from sequence of $s \times t$ ($s = 1 \ldots M,\ t = 1 \ldots N$) perspective images captured in horizontal and vertical directions. Each perspective image consists of $i \times j$ ($i = 1 \ldots m,\ j = 1 \ldots n$) pixels. The size of the hogel images is M × N, whereas their number is given by m × n. The pixels in the hogel images are arranged in the order of capture of perspective images along horizontal and vertical axes. All the pixels at the same location of perspective images are extracted to form a new matrix H_{ij}, which denotes a parallax-related image. The hogel image is composed from (i, j)-th pixels in all perspective images as follows:

$$H_{ij}(s,t) = P_{st}(i,j),\ \ s = 1 \ldots M, t = 1 \ldots N; i = 1 \ldots m, j = 1 \ldots n \tag{1}$$

The hogel image H_{ij} is displayed on a SLM and recorded in a focal plane of an objective lens as an elemental hologram by means of a reference beam. In the focal plane of the writing lens system the Fourier transform of the hogel image is obtained as desired size.

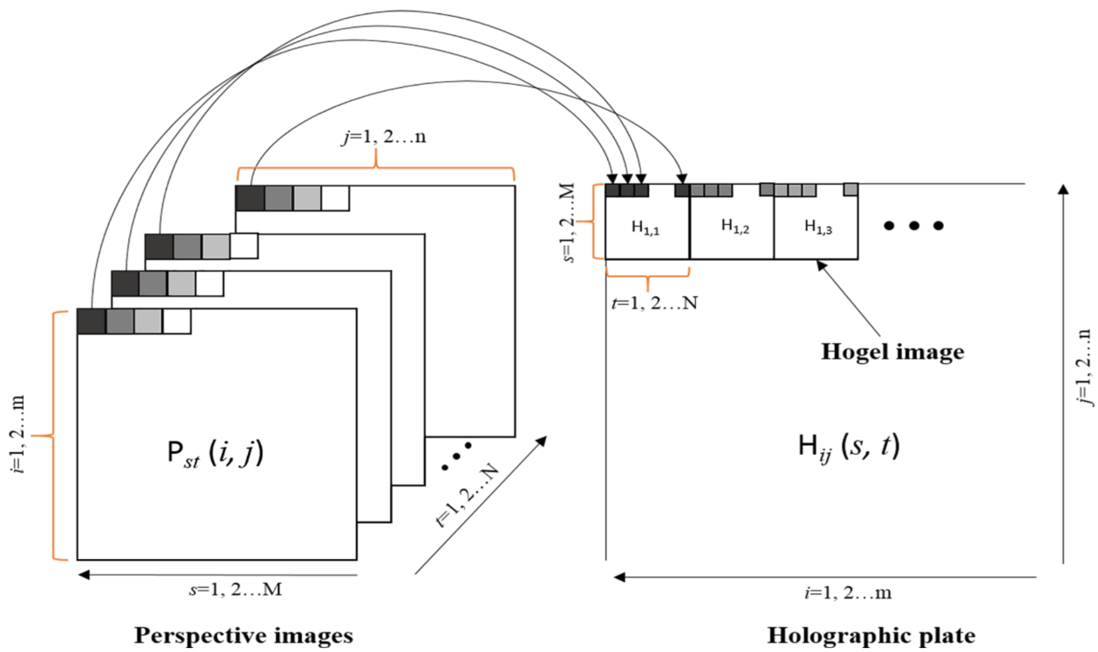

Figure 2. Re-arrangement process of hogel image generation from rendered perspective images.

When moving from side to side at the reconstructed image plane, viewer's eye can see parallax information of the object. When the reconstructed wave is modulated by a hogel, it yields complex amplitude $O(x,y) = A(x,y)\exp[j\phi(x,y)]$, where $A(x, y)$ and $\varphi(x,y)$ are amplitude and phase distributions, respectively.

2.2 Control system

We developed control graphic user interface (GUI) in LabVIEW software for automatic recording of holographic stereogram. The control system is able to works with SLM display, X-Y translation stage and electrical shutter to control the exposure time at the same time. The user can put additional parameters such as exposure time, number of hogels to be printed, settling time, waiting time and hogel image path on the SLM in LabVIEW software. The principle of printing algorithm is shown in Fig 3. Figure 4 shows the control GUI appearance in LabVIEW software. A design of printing method was to print a horizontal row of pixels, from left to right until the whole horizontal line is exposed, and then move up vertical stage across by one pixel then returning the horizontal stage back to the left so on continuously printing hogels. This printing method is much faster than moving the horizontal or vertical stage back to the original position.

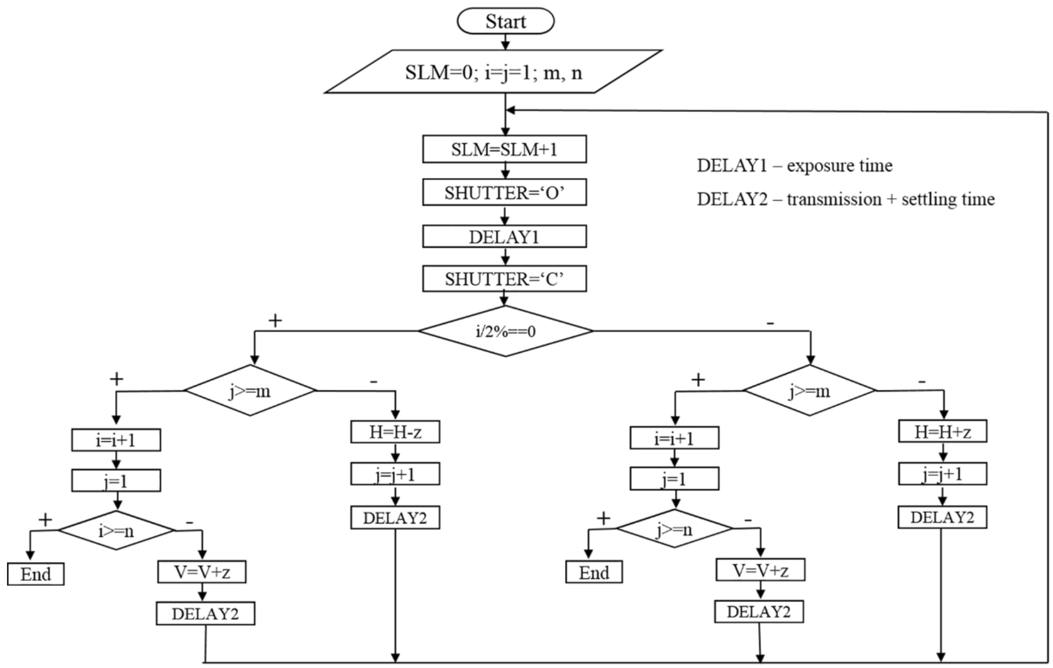

Figure 3. Printing algorithm for automatic recording of the holographic stereogram.

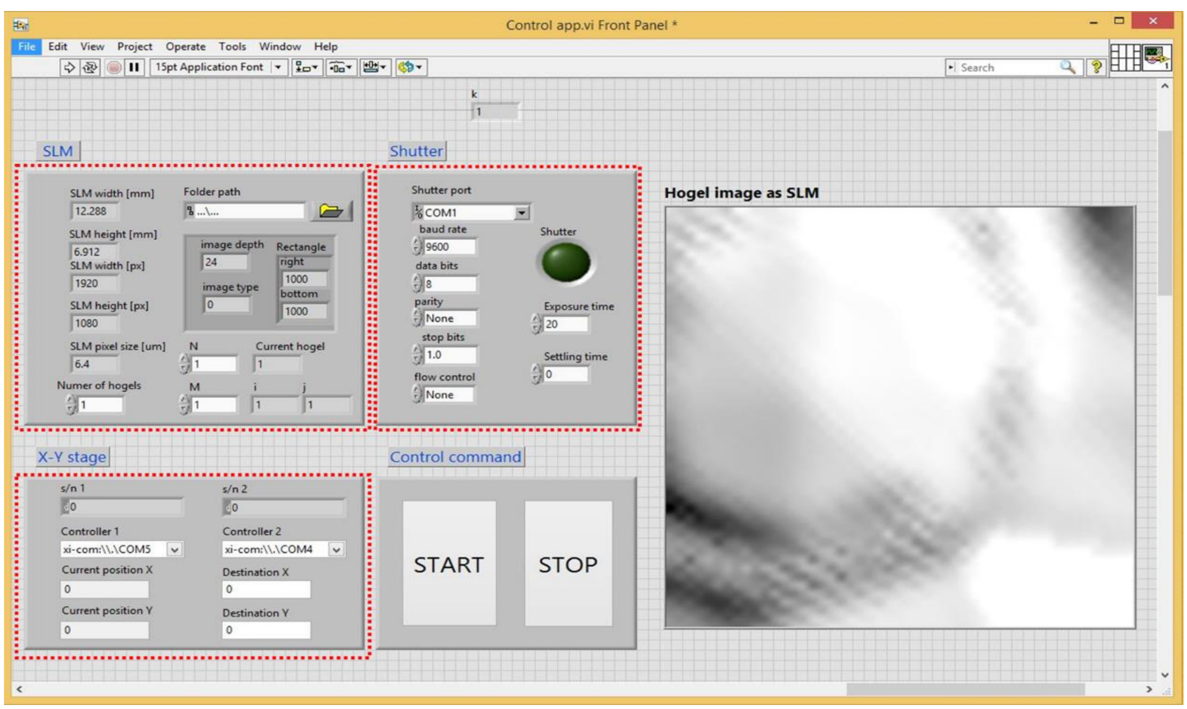

Figure 4. Control software for holographic stereogram printing.

3. EXPERIMENTAL IMPLEMENTATION

3.1 Computational implementation

To verify the performance of the 3D content generation platform, we did numerical simulation for the synthesized holographic stereogram. The perspective images of the computer-generated 3D object are captured by re-centering camera method in Blender modeling software and rendered directional information from 3D object "Monkey head and Cube" within a FOV of 30°. The FOV of the viewer zone must be matched with the writing lens FOV. The hologram plane was synthesized from 100 × 100 hogels and each hogel image consists of 100 × 100 pixels according to the rearrangement process. The perspective images were rearranged to form 10,000 separate-parallax images. The generated hogel images were expanded 12 times before loading to the SLM. In Fig 5(a) and 5(b) illustrates the computer graphic 3D object and 9 examples of perspective images in different viewing positions rendered in Blender open-free software. Figure 6 presents the full parallax holographic stereogram which is composed from rearranged hogel images. In Fig. 6, the transformation technique in Eq. 1 is applied to generate hogel images from the perspective images to print distortion free 3D images. The generated 10,000 hogel images were used as an input data for SLM display to compose holographic stereogram.

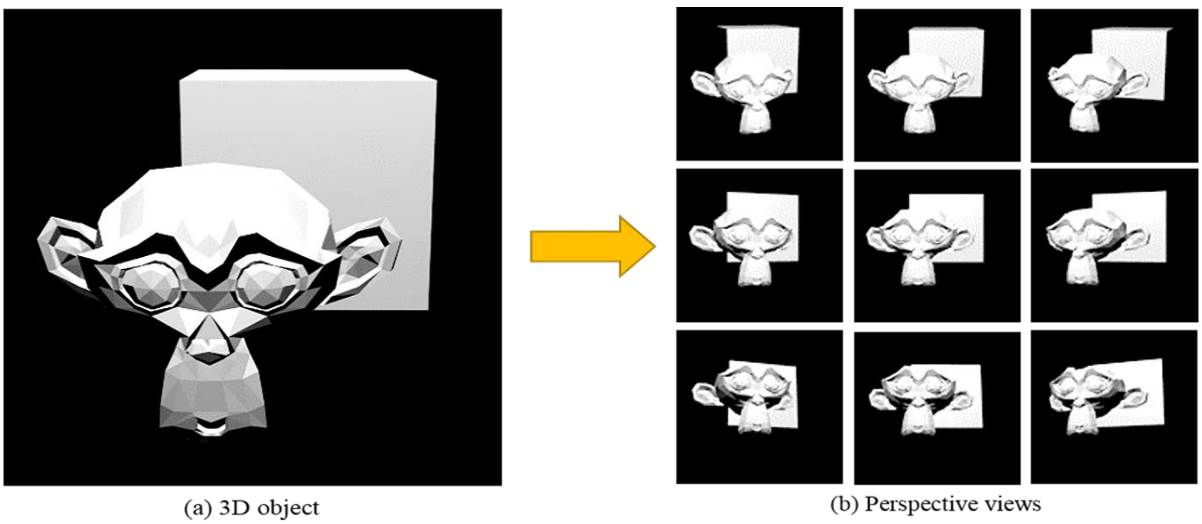

Figure 5. (a) 3D model; (b) example 9 perspective images in different viewing position.

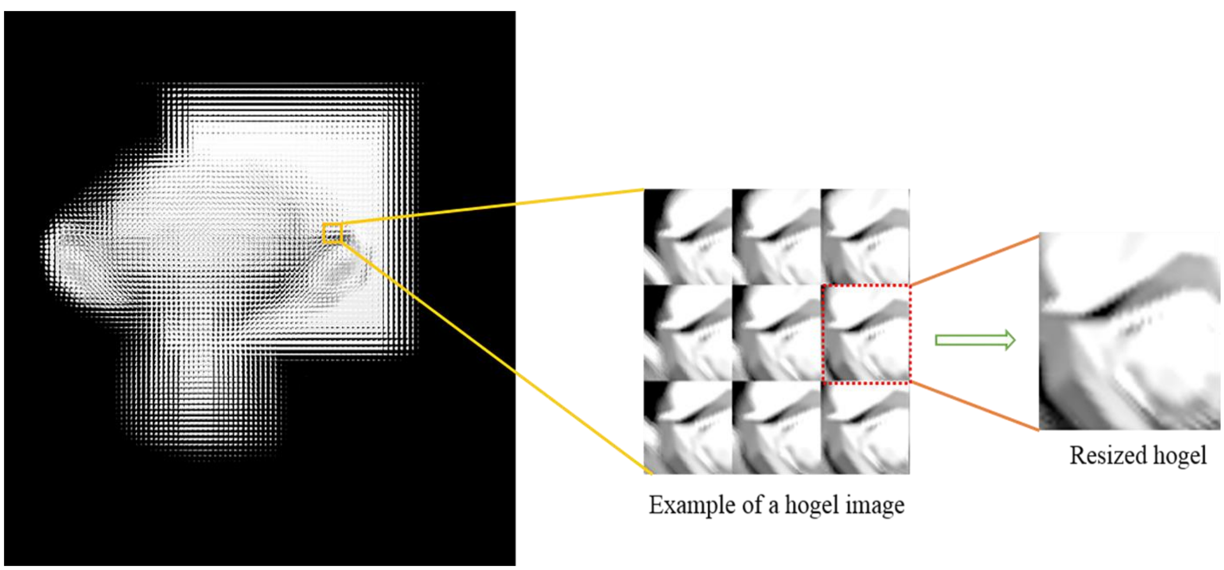

Figure 6. The numerical simulation of hogel rearrangement process: Full parallax holographic stereogram composed from parallax-related images.

Each hogel image acts as directional emitter and displayed on the SLM to be recorded as an elemental hologram using our LabVIEW based content generation platform. From holographic stereogram presented in Fig. 6, the viewer perceives intensity provided by all hogels within the angular intensity distribution related to the particular viewer position and stereoscopic vision due to the binocular parallax. Because the viewer's left and right eyes correspond to the different viewing position and capture different images from the hogel images.

3.2 Optical implementation

The optical setup of the holographic stereogram printing system is shown in Fig. 6. 532 nm wavelength laser was used as light source. The beam from a laser is divided into two beams and the intensity ratio of two beams were adjusted by first half-wave plate. The p-component of the laser light is transmitted through the beam splitter, while the s-component is reflected. The object beam is expanded by L1 and illuminates the SLM. The object beam is spatially modulated by the hogel image which is displayed on SLM. The SLM used in the system is a LETO Phase-only modulator (HOLOEYE Photonics AG), which is reflective type SLM with 1920 × 1080 pixels with a pixel pitch of 6.4 µm. Displayed image is demagnified by lenses L3 and L4 and exposed on a photo-sensitive material. The focal length of the lens L3 and L4 are 85 mm and 25 mm respectively. The beam's polarization is orientated in the direction such that all of the beam's energy is directed by the polarizing beam splitter to the LCOS display system. There were two apertures close to the holographic plate from both side to ensure only the square area of the holographic plate exposed. The reference beam is incident through long focal length lenses L1 and L2 on the holographic plate from opposite side at 45 degrees. The hogel images are interfered with reference beam and recorded as an elemental hologram. Through such procedure, each hogel is recorded at the desired position. The exposure time is controlled using an electrical shutter. The holographic plate was installed on a motorized X-Y stage whose positioning was both along the horizontal and vertical directions.

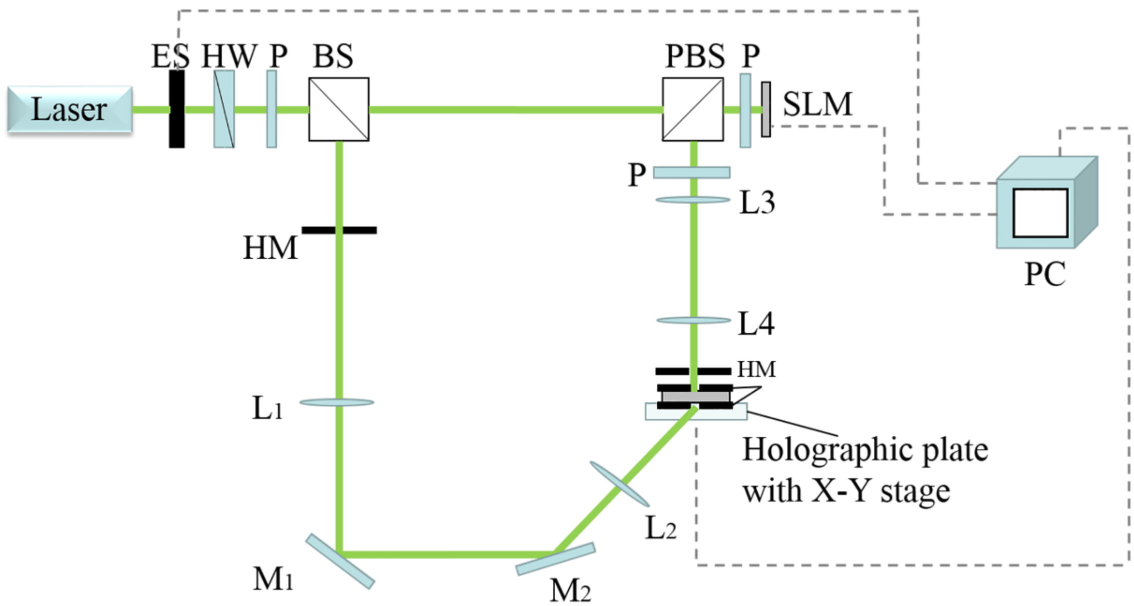

Figure 7. Optical setup of holographic stereogram printer system.

Reconstructed image from different perspectives of the holographic stereogram under white light illumination is shown in Figure 8. The reconstructed parallax image is reconstructed in a FOV of 30 degree. Holographic stereogram in Fig. 8 is synthesized from 50 x 50 hogel, each hogel size is 1mm x 1mm. The distance from the 3D scene to the hologram plane and the hogel size are the two parameters that affect the reconstructed image's resolution. When the stage moves, the motors generate more vibrations so it is required to have a higher mechanical stability. This affects the reconstructed image quality. To increase the resolution of a hologram by changing a pixel size of 1 mm to 0.5 mm, we made improvement for increasing the resolution of the hologram and reduce hogel size. Also the increased mechanical stability provides more quality image. Figure 9 shows the photograph taken from the different perspective views of holographic stereogram after improvements.

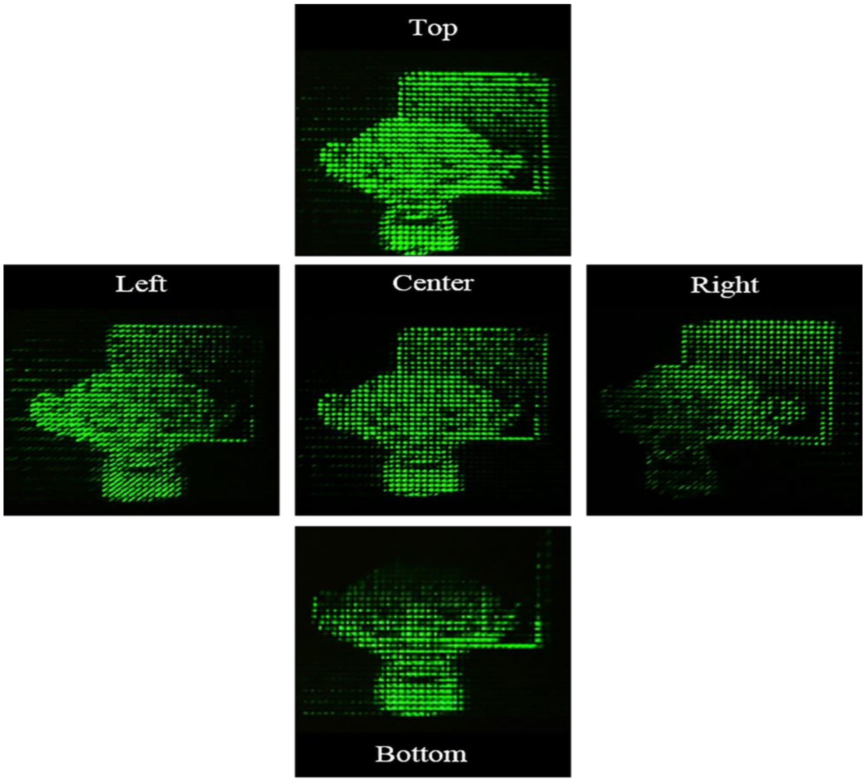

Figure 8. Reconstructed holographic stereogram from different perspectives with 1mm x 1mm pixel size before improvements.

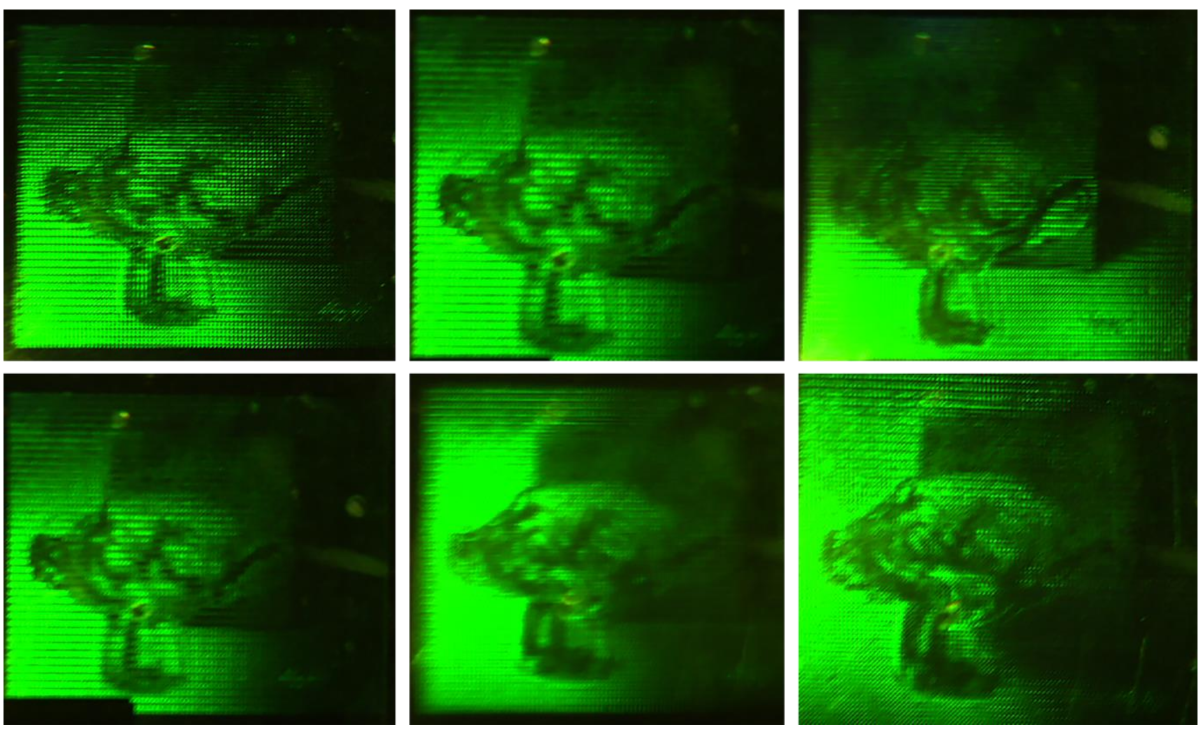

Figure 9. Photograph taken from different perspectives of holographic stereogram with 0.5mm x 0.5mm pixel size.

4. CONCLUSION

A design of digital content generation simulator based on integration of phase-only spatial light modulator (SLM) and LabVIEW software for holographic stereogram printer is presented. By regarding the parts in the simulator, a corresponding digital content can be generated. The holographic stereogram is synthesized as a two-dimensional array of hogel images. Reflective-type phase-only SLM displays the perspective images generated by the developed LabVIEW based simulator for each hogel image printing. By updating the hogel image on the SLM and using a motorized X-Y translation stage, the full parallax holographic stereogram was printed on the holographic light sensitive material. The experimental results indicated that the small hogel size is required to increase the reconstructed image quality. However, hogel size reduction leads to a reduction in the angular resolution of a synthesized holographic stereogram from experiment. We expect that proposed simulator will be efficient 3D content generation platform for holographic stereogram printer.

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