Reconstruction Improvement in Integral Fourier Holography by Micro-Scanning Method

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***Abstract*—Although integral holography has many promising advantages in the field of 3D imaging, the resolution of reconstructed holographic image is still limited by the insufficient information captured. To improve the reconstruction quality, an integral Fourier holographic imaging method based on micro-scanning of the micro-lens array is proposed in this paper. The micro-scanning of the micro-lens array can increase the sampling rate in spatial frequency domain and the information of the generated Fourier hologram, which will eventually eliminate the overlapping effect in the reconstructed 3D image. Experiments for different micro-scanning modes are carried out to verify the feasibility of the proposed method and to show that the reconstruction quality is effectively enhanced.**

***Index Terms*—3D imaging, holography, integral imaging, micro-scanning.**

I. Introduction

ALTHOUGH holography has been considered as a perfect method to generate authentic 3D illustration, its interfering nature requires an extremely stable optical system and intense light sources with narrow bandwidth. To improve the flexibility of conventional holography, several methods of capturing the 3D information without using coherent optics have been proposed [1]–[6]. These include hybrid interfaces between integral imaging and holography [4]–[7]. In those methods, a series of multiple view projections of the 3D scene obtained under incoherent white-light illumination condition are processed to generate a digital hologram. This viewpoint-projection holographic technique has been used in many application areas, such as real-time 3D holographic video acquisition and video conferencing, 3D biomedical holographic imaging and 3D object recognition etc. To make the 3D information acquisition of this technique easier, a method called integral holography has been proposed [5]. In this technique, which is based on 3D integral imaging, a micro-lens array is used for capturing the multiple view images [8]–[11]. Furthermore, this method has been extended to generating integral hologram in a straightforward way by using orthographic projection geometry [6].

The resolution of the 3D image reconstructed from an integral holographic system is still limited by the low sampling rate and the insufficient information captured. An in-depth quantitative analysis of the effects of system parameters on the 3D reconstructed images has been conducted [12]. Also, the space-bandwidth product of an integral holographic system has been derived in our previous paper to characterize its information transfer capacity [13]. Specifically, it can be found that the sampling interval in space domain is determined by the lens pitch, whereas the sampling interval in spatial frequency domain is determined by the pixel pitch. Therefore, insufficient sampling rate in space and spatial frequency domain will lead to aliasing and overlapping effects in the reconstructed 3D image. Methods for synthesizing intermediate elemental images (EIs) and orthographic projection images were proposed to eliminate both of these effects [13]. However, the amount of captured information is not improved with such methods. To increase the sampling rate in space domain, a moving array lenslet technique (MALT) [14], [15] was applied to integral holography [12]. However, the number of pixels in any EI is still limited by the detector pixel size.

In this paper, we propose an integral Fourier holographic imaging method based on micro-scanning of a micro-lens array to enhance the reconstruction quality. Note that unlike the MALT method, the micro-scanning is applied here to enhance the resolution within each EI. Experimental results show that with the proposed method, the image quality of the 3D reconstruction has been improved significantly.

This paper is organized as follows. In Section II we propose the micro-scanning based integral Fourier holographic imaging method. In Section III we analyze the effects of the micro-scanning on the sampling property, the generated hologram and the reconstruction of an integral Fourier holographic system. In Section IV, experiments are conducted to verify the proposed methods. Finally in Section V we summarize the main outcomes of this paper.

II. Integral Fourier Holographic Imaging Method Based on Micro-Scanning

In an integral Fourier holographic system (IFHS), the micro-lens array usually has a large number of lenses with a small lens pitch. A digital camera captures the images on the image

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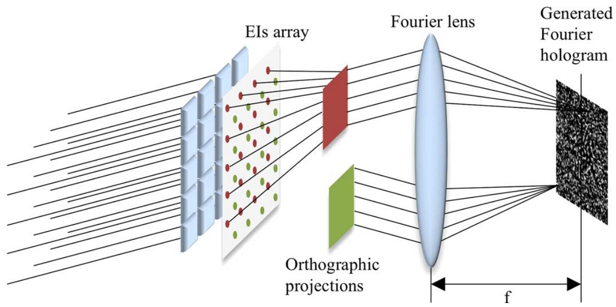

Fig. 1. Integral Fourier hologram generated from multiple orthographic projections.

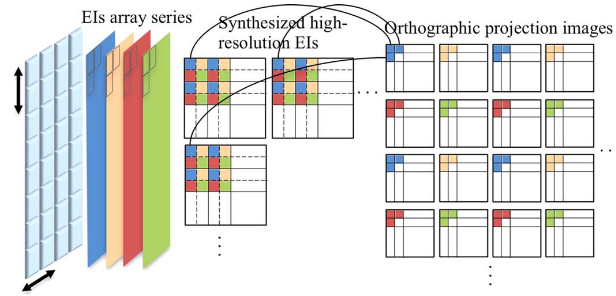

Fig. 2. Scheme of the micro-scanning method in integral holography.

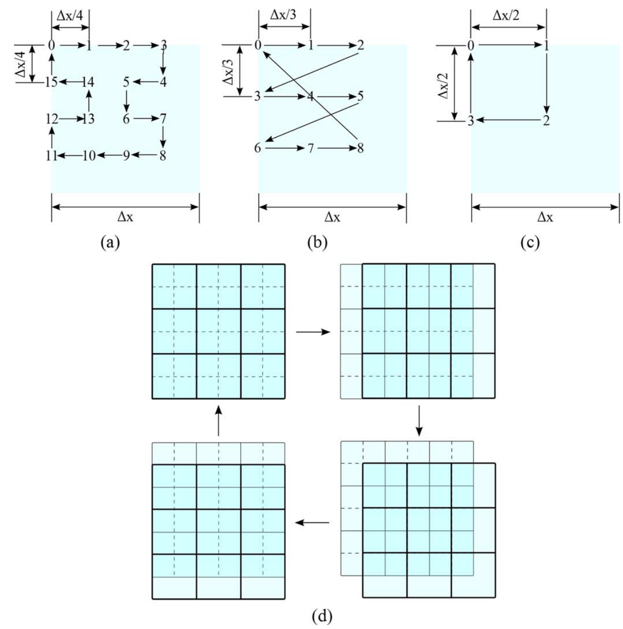

Fig. 3. Typical micro-scanning working modes. (a) 4×4 steps. (b) 3×3 steps. (c) 2×2 steps. (d) Subpixel displacements in 2×2 steps.

plane or focal plane of the micro-lens array. The small lens pitch and the pixel pitch of digital camera may limit the resolution of the captured EIs and lead to a degraded 3D image quality in the reconstruction. To improve the resolution of each EI, an integral Fourier holographic imaging method based on micro-scanning is proposed with the introduction of the principle of orthographic projection based integral Fourier holography.

The principle for generating an integral Fourier hologram from orthographic projection images is shown in Fig. 1. First, multiple perspective projections of a 3D scene, i.e., EIs, are captured with a micro-lens array. Pixels of the same position in each EI are the focus points of a parallel light-beam proceeding from the 3D scene. Thus, the entire information from the same direction of the 3D scene can be obtained by gathering these pixels to form an orthographic projection image. Then, each orthographic projection is multiplied by a phase factor of the corresponding slanted plane wave. Each product is integrated into a single complex value that is regarded as a pixel in the generated hologram. The position of the pixel in the hologram corresponds to the image position of the orthographic projection image in the orthographic projection images array. By applying this process to all of the orthographic projection images, a digital 2D Fourier hologram can be generated. The mathematical process of generating the hologram is

$$H(u,v) = \iint^{O_{u,v}} (x,y) \exp\left[j\frac{2\pi}{\lambda f}(ux+vy)\right] dxdy \quad (1)$$

where $O_{u,v}(x,y)$ is the (u,v)th orthographic projection image, λ is wavelength and f is the focal length of the Fourier lens.

To increase the effective number of pixels in each EI, the micro-scanning technique is applied to this IFHS. As shown in Fig. 2, the micro-scanning method is performed by shifting the micro-lens array with sub-pixel displacements. Then, the multiple EIs arrays are interlaced to synthesize a single high-resolution EIs array. The synthesized high resolution EIs are used for generating a new series of orthographic projection images. The number of orthographic projection images is increased according to the scanning steps. With these orthographic projection images, a denser Fourier hologram will be generated.

Fig. 3 shows several typical micro-scanning working modes that are used in practice [16], [17]. Each mode corresponds to a sub-pixel displacement of the EIs array over the detector on a square grid, such as 2×2, 3×3, or 4×4 positions with its horizontal and vertical step sizes of one-half, -third, or -fourth of the detector pixel pitch, respectively. Assuming that both the horizontal and vertical pixel pitch is Δx and the micro-scanning step is $n \times n$, the displacement in horizontal and vertical directions could be calculated as $\Delta x/n$, and the number of EIs arrays is n^2.

Fig. 3(d) shows an example of using a four steps micro-scanning working mode to obtain four EIs with one of the micro-lenses.

III. Effects of Micro-Scanning on an Integral Fourier Holographic System

The effects of the micro-scanning technique on an IFHS and its 3D reconstruction are analyzed in this section.

As shown in Fig. 4, at the focal plane of the micro-lens array, every pixel captures a collection of the parallel rays. The angular interval of two adjacent projection directions $\Delta\alpha$ is determined by the pixel pitch Δx. By moving the micro-lens with a displacement of $(1/2)\Delta x$, the parallel rays from $(1/2)\Delta\alpha$ direction are projected to one of the two adjacent pixels. Analogously, every pixel in the EI that imaged by the moved micro-lens has captured the parallel light from a middle direction between the angular intervals with a slightly angular difference of $(1/2)\Delta\alpha$. Therefore, the micro-scanning of the

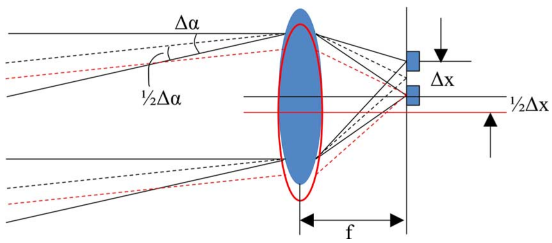

Fig. 4. Scheme of the sub-pixel sampling by micro-scanning.

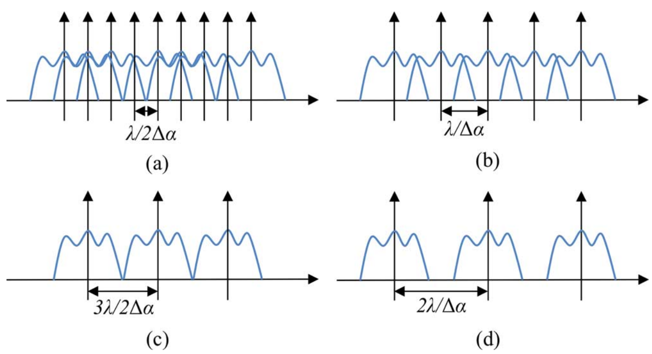

Fig. 5. Repetition periods of the reconstruction from (a) single step, (b) 2 × 2 steps, (c) 3×3 steps, and (c) 4×4 steps micro-scanning.

micro-lens array with a displacement of $(1/n)\Delta x$ can increase the angular sampling rate by n^2.

In an orthographic-projection based IFHS, the angular interval determines sampling rate in spatial frequency domain since the generated hologram is discretized with [12]

$$\Delta u = 2f\Delta\alpha. \tag{2}$$

According to the sampling theory, the 3D scene will be reconstructed with a repetition period of

$$p = \frac{\lambda f}{\Delta u} = \frac{\lambda}{2\Delta\alpha}. \tag{3}$$

Therefore, if the angular interval is large, an overlapping effect of multiple 3D scenes may occur in the reconstruction as shown in Fig. 5(a). However, with the proposed method, the angular interval $\Delta\alpha$ will be reduced to $(1/n)\Delta\alpha$, and the hologram is discretized with

$$\Delta u' = \frac{2f\Delta\alpha}{n}. \tag{4}$$

Accordingly, the repetition period of the reconstructed 3D scene will be enlarged to

$$p' = \frac{\lambda f}{\Delta u'} = \frac{n\lambda}{2\Delta\alpha} \tag{5}$$

which is n times large as the original repetition period. Fig. 5(b)–(d) demonstrates the repetition periods of the reconstruction from four steps, nine steps and sixteen steps micro-scanning modes. It can be seen that the repetition period increases with the scanning steps and the overlapping effect will be alleviated, or even be eliminated.

Additionally, as shown in Fig. 1, the resolution of each EI is equal to the number of orthographic projection images, since only one pixel is exacted from each EI to form an orthographic projection image. Also, the number of orthographic projection images is equal to the resolution of the hologram. Therefore, the resolution of the generated hologram is the same as the resolution of each EI, which means capturing a set of low-resolution EIs will lead to a low-resolution hologram. With the proposed method, the pixel number in each EI will be increased by n^2. As a result, the pixel pitch in the generated Fourier hologram, i.e., the sampling interval in spatial frequency domain, will be reduced to $\Delta u/n$. Therefore, a denser Fourier hologram with more information can be generated.

Let us assume that a mechanical movement error occurs during the micro-scanning. For example in Fig. 4, instead of $(1/2)\Delta \mathrm{x}$, a displacement of $\Delta \mathrm{d} \in [0, \Delta \mathrm{x}]$, $(\Delta \mathrm{d} \neq (1/2)\Delta \mathrm{x})$ is the moving step of a four steps micro-scanning. If $\Delta \mathrm{d}$ equals to 0 or $\Delta \mathrm{x}$, the micro-scanning performs corresponding to enlarging each EI by repeating all of the pixels. It can preliminary alleviate the overlapping effects, which has been used in common integral holography [6], [12], [13]. If $0 < \Delta \mathrm{d} < \Delta \mathrm{x}$, $(\Delta \mathrm{d} \neq (1/2)\Delta \mathrm{x})$, the micro-scanning leads to an uneven sampling of the 3D objects by pixels in every synthetic high-resolution EI. However, each pixel captured by the micro-scanning step can still be considered as an intermediate angular sampling, which could eventually alleviate the overlapping effects. Only that the increased intermediate angular samplings is not precisely from $(1/2)\Delta\alpha$ direction. Thus, the tolerable micro-scanning displacement of four steps is $\Delta \mathrm{d} \in [0, \Delta \mathrm{x}]$. For nine steps, the tolerable micro-scanning displacement is $\Delta \mathrm{d} \in [0, \Delta \mathrm{x}/2]$ and for sixteen steps, the tolerable micro-scanning displacement is $\Delta \mathrm{d} \in [0, \Delta \mathrm{x}/3]$. Therefore, the micro-scanning based IFHS setup is not sensitive to the movement error if the micro-scanning displacement of $\mathrm{n} \times \mathrm{n}$ steps is $\Delta \mathrm{d} \in [0, \Delta \mathrm{x}/(\mathrm{n}-1)]$.

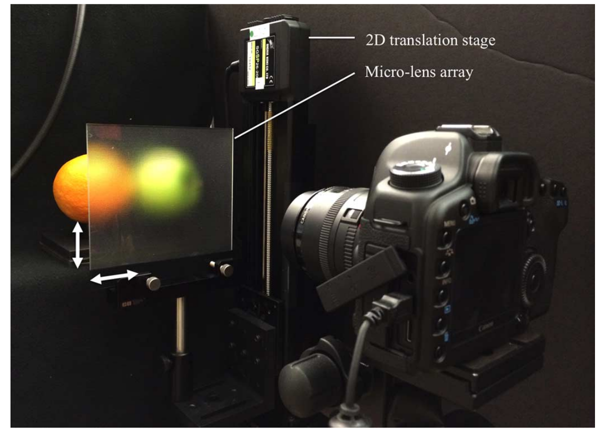

Fig. 6. Experimental setup of a micro-scanning based integral holographic system.

IV. Experimental Results

To verify the effectiveness of the micro-scanning based IFHS, we arranged the experimental setup shown in Fig. 6. The 3D scene consists of a green apple and an orange, which are located at about 10 cm and 16 cm from the micro-lens array, respectively. The scene is illuminated by two illuminators of incoherent white-light from different directions to reduce the unwanted light passing through the micro-lens array. But in order

TABLE I
SYSTEM PARAMETERS OF THE EXPERIMENTAL SETUP

Micro-lens array	Focal length	3.3mm
	Numbers of micro-lens (used)	148(H)×94(V)
	Lens pitch	1mm
Camera	Focal length	50mm
	Pixel size	6.25μm
Micro-scanning displacements performed by 2D translation stage	1 step (without moving)	0μm
	4 step	19.25μm
	9 step	12.80μm
	16 step	9.60μm

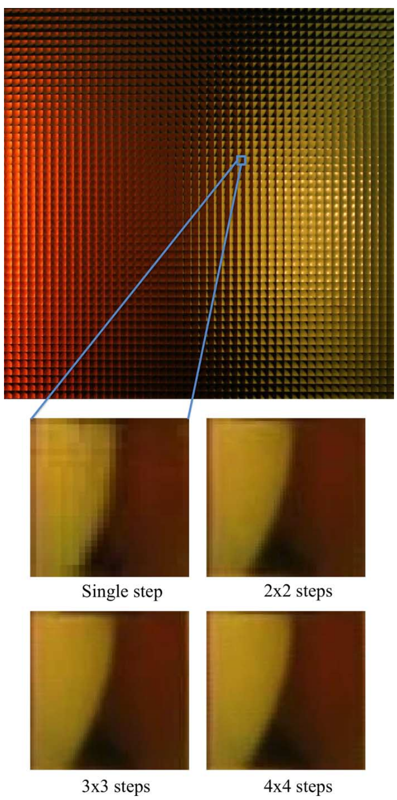

Fig. 7. Part of the low-resolution EIs array and the high-resolution EIs synthesized by micro-scanning method.

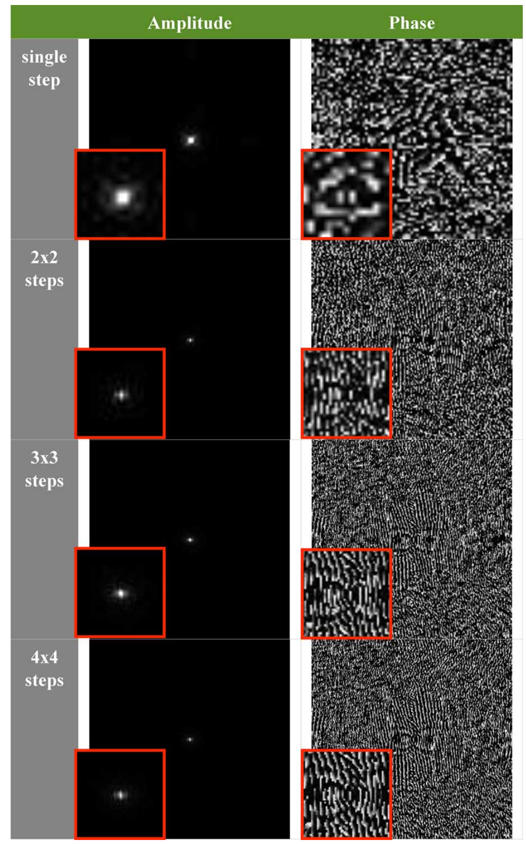

Fig. 8. Integral Fourier hologram (red component) generated with different micro-scanning modes.

to show the whole experimental setup in Fig. 6, the day lamp is used and the illuminators have been removed cause it will block the scene. The micro-lens array is controlled by a 2D translation stage to preform the horizontal and vertical shifting. A digital camera is used to capture the EIs on the focal plane of the micro-lens array.

Table I illustrates the parameters of the experimental setup. Since each EI includes 26×26 pixels and the micro-lens pitch is 1 *mm*, the pixel pitch on the focal plane of the micro-lens array can be calculated as $1\ \mathrm{mm}/26 \approx 38.45\ \mu\mathrm{m}$. Therefore, the sub-pixel displacement of $\mathrm{n} \times \mathrm{n}$ step micro-scanning will be $38.45/\mathrm{n}\ (\mu\mathrm{m})$. The minimum shift unit of the 2D translation stage is 50 *nm* and the micro-scanning displacements preformed by the translation stage are shown in Table I.

Fig. 7 shows the EIs array captured by a single step, and also the synthetic EIs generated by multiple steps micro-scanning. It can be seen that, comparing to the low-resolution EI captured by a single step, the resolution of EIs are increased with micro-scanning. Note that to preliminary alleviate the overlapping effect in the reconstruction, every EI in the experiment has been enlarged three-times by interpolation after being synthesized with micro-scanning method. However, different from the micro-scanning, the interpolation does not increase the sampling rate or introduce any extra information.

Fig. 8 shows the generated holograms of the red color component of the 3D scene. The central parts of the holograms are enlarged to show its density. It can be found that the density of the holograms increases with the increase of the scanning steps in both of the amplitude and phase components.

The 3D objects can be reconstructed with the generated integral hologram digitally by using Fourier transform and Fresnel propagation algorithm or optically by encoding the complex matrix of the integral hologram into a computer-generated hologram (CGH) for display devices [2], [5]. The computational reconstruction is implemented here since it would be easier to compare the repetition periods of different scanning steps in the reconstructed images. Also, it would be easier to reconstruct a colorful scene. To reconstruct the 3D scene, a 2D inverse Fourier transform is applied to each color component of the holograms to generate the corresponding color reconstruction in the reference depth plane. Then, Fresnel propagations are applied to the reconstruction in the reference depth plane to calculate the reconstructions in other depth planes along the optical

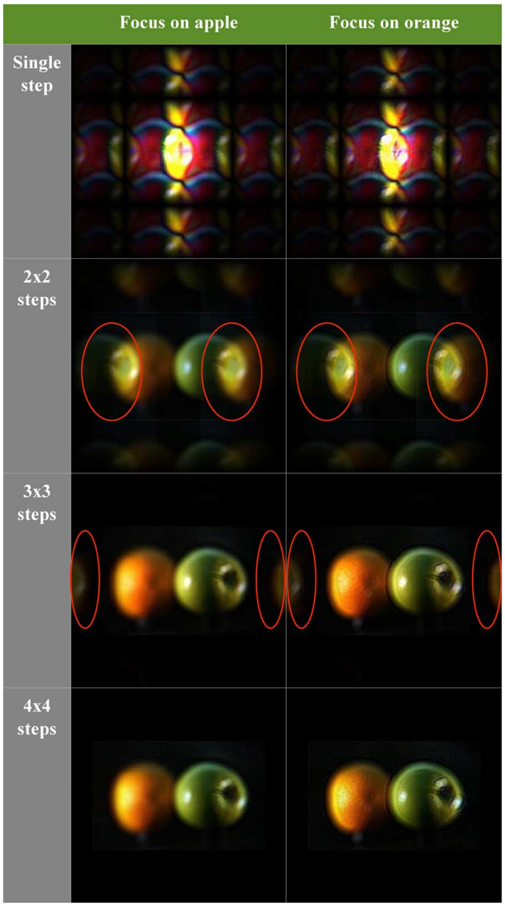

Fig. 9. 3D images reconstructed from the integral Fourier holograms generated with one step, 2×2 steps, 3×3 steps and 4×4 steps micro-scanning.

axis of the 3D scene. The R, G, B component of the reconstruction are combined to obtain the colorful reconstructed images.

The reconstruction results are shown in Fig. 9. The left column shows the reconstructed images that are focused on the apple, and the right column shows the reconstructed images that are focused on the orange. It is noticeable that with the sixteen steps micro-scanning method, the repeated images disappear. Therefore, with the proposed method, the overlapping effects caused by insufficient sampling rate in spatial-frequency domain are eliminated and the 3D image quality is improved.

V. Conclusion

In this paper, we applied a micro-scanning technique to the IFHS to overcome the degradation caused by insufficient sampling rate in spatial frequency domain. It has been found that with our method, the angular sampling interval is reduced and the density of the generated Fourier hologram is improved. As a result, the overlapping effects in the reconstructed 3D image are eliminated and the image quality gets enhanced. Experimental results have proved the elimination of the overlapping and the improvement of the degraded 3D images.

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