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Computational volumetric reconstruction of integral imaging with improved depth resolution considering continuously non-uniform shifting pixels

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A B S T R A C T

In this paper, we propose a new computational volumetric reconstruction technique of three-dimensional (3D) integral imaging for depth resolution enhancement by using non-uniform and integer-valued shifting pixels. In a typical integral imaging system, 3D images can be recorded and visualized using a lenslet array. In previous studies, many computational reconstruction techniques such as computational volumetric reconstruction and pixel of elemental images rearrangement technique (PERT) have been reported. However, a computational volumetric reconstruction technique has low visual quality and depth resolution because low-resolution elemental images and uniformly distributed shifting pixels are used for reconstruction. Although PERT can enhanced the visual quality of the 3D images, the size of the reconstructed 3D images is different from the original scene. On the other hand, our proposed method uses non-uniformly distributed shifting pixels for reconstruction instead of uniformly distributed shifting pixels. Therefore, the visual quality and depth resolution may be enhanced. Finally, our experimental results show the improvement of depth resolution and visual quality of the reconstructed 3D images.

1. Introduction

Three-dimensional (3D) image sensing and visualization of integral imaging has been studied for several applications including unmanned autonomous vehicle system, pattern recognition, 3D entertainments, medical imaging, defense, and so on [1–17]. Integral photography or integral imaging was first proposed by Lippmann in 1908 [1]. It has been a popular 3D technique since it can provide full-color, full-parallax, and continuous viewing points without special glasses and coherent light source. In addition, using computational reconstruction [9], 3D information of objects (i.e., 3D point cloud of objects) can be obtained.

A typical integral imaging system is composed of two primary processes: pickup and reconstruction (or display) processes. In the pickup stage, the light rays coming from 3D objects are recorded through a lenslet array on an image sensor such as charge-coupled device (CCD). They are multiple 2D images with different perspectives called as elemental images. In the reconstruction or display stage, a homogeneous lenslet array used in the pickup process is positioned in front of elemental images. Then, the 3D image is formed in free space by back-propagation of light rays for each elemental image.

Recently, many computational volumetric reconstruction techniques are reported; computational volumetric reconstruction [10], 3D profilometry [11], pixel of elemental images rearrangement technique (PERT) [12], PERT with projected empty space (PERTS) [13], and so on [14–17]. In general, computational volumetric reconstruction is used because of its simplicity. In this method, each elemental image is back-projected through the virtual pinhole array on the reconstruction plane. Since typical computational volumetric reconstruction uses the pixilated process and the number of shifting pixels for reconstruction is the fixed integer value and uniformly distributed, the depth resolution of the reconstructed 3D image is not sufficient. Further, the reconstructed 3D images have poor visual quality when elemental images with low resolution are used. To solve these problems, a new reconstruction method is required. Therefore, in this paper, we propose a new computational volumetric reconstruction method with improvement of depth resolution and visual quality for the reconstructed 3D images considering continuously non-uniform shifting pixels when elemental images with low resolution are used. In our proposed method, we use non-uniformly distributed and integer-valued shifting pixels for reconstruction. Thus, the depth resolution can be improved compared with the computational volumetric reconstruction method. Also, the visual quality of the recon-

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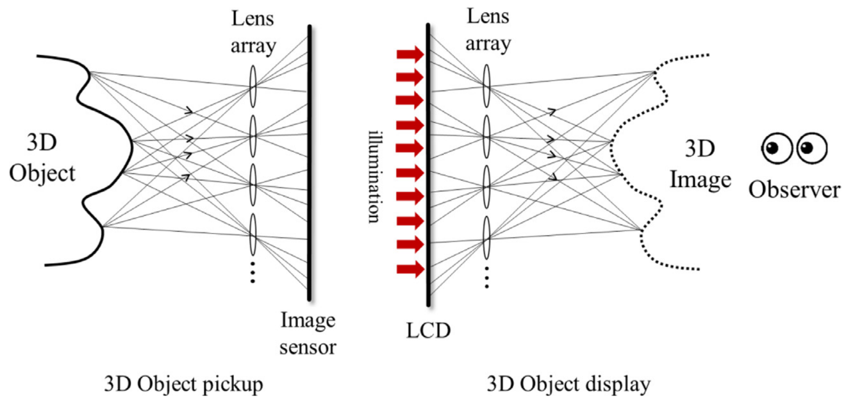

Fig. 1. Concept of conventional integral imaging system.

structed 3D images can be even enhanced than the conventional reconstruction.

This paper is organized as follows. In Section 2, we briefly present the principle of computational volumetric reconstruction for integral imaging. In Section 3, we explain our proposed method. Then, we show the experimental results to prove that our method can enhance the depth resolution and visual quality compared with the computational volumetric reconstruction method in Section 4. Finally, we conclude with summary in Section 5.

2. Computational volumetric reconstruction of integral imaging

In this section, we briefly describe integral imaging system, including pickup and computational volumetric reconstruction processes. In this system, 3D images can be recorded and visualized by the lenslet array under incoherent illumination conditions as shown in Fig. 1.

In pickup process, each voxel of the 3D objects is mapped on imaging plane of the lenslets array and recorded by CCD camera. Consequently, each voxel of the 3D objects leads to form all the pixels of elemental images. Since the number of pixels for the image sensor is divided by the number of lenslets, each elemental image has low lateral resolution. Thus, to enhance the lateral resolution of each elemental image, synthetic aperture integral imaging (SAII) [18] as depicted in Fig. 2 can be utilized.

In reconstruction process, there are various computational reconstruction techniques [10–17]. In this paper, we consider computational volumetric reconstruction only [10] since it is the most similar with optical reconstruction in integral imaging. The elemental images obtained in pickup process are used in computational volumetric reconstruction as depicted in Fig. 3. In the reconstruction process, the homogeneous lenslet array in the pickup process is used. By back-propagation of the elemental images through the lenslet array in display process, the 3D images are formed in free space. In computational volumetric reconstruction, each elemental image is back-projected through the virtual pinhole array and magnified with magnification ratio $M = z_d/f$, where z_d is the desired reconstruction depth and f is the focal length of the virtual pinhole. Finally, the reconstructed 3D image can be obtained by averaging all corresponding pixels of elemental images at the reconstruction depth. The procedure of computational volumetric reconstruction is follows [10]:

$$\Delta x_s = \frac{N_x \times p_x \times f}{c_x \times z_d}, \qquad \Delta y_s = \frac{N_y \times p_y \times f}{c_y \times z_d} \tag{1}$$

$$\Delta x_p = \lceil \Delta x_s \rfloor, \qquad \Delta y_p = \lceil \Delta y_s \rfloor \tag{2}$$

$$I(x, y, z_d) = \frac{1}{O(x, y, z_d)} \sum_{k=0}^{K-1} \sum_{l=0}^{L-1} E_{kl}(x + k\Delta x_p, y + l\Delta y_p) \tag{3}$$

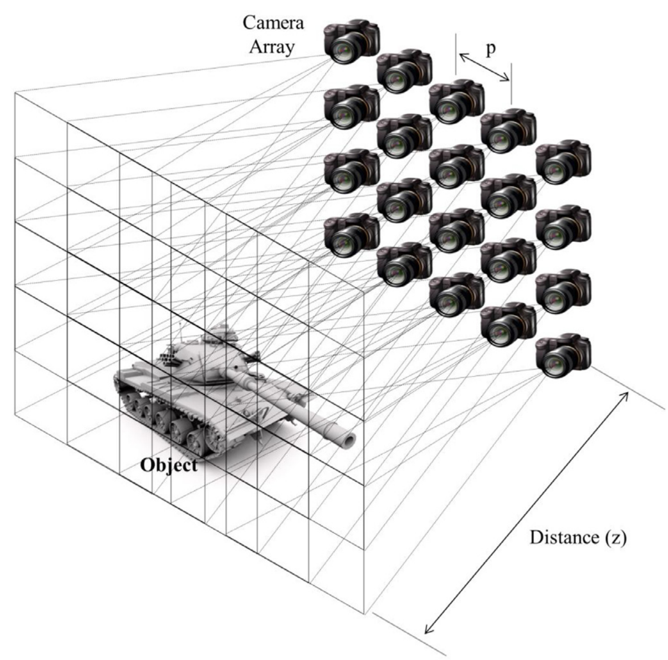

Fig. 2. Synthetic aperture integral imaging (SAII).

where N_x, N_y are the number of pixels for each elemental image, p_x, p_y are the pitch between the virtual pinholes, $I(x, y, z_d)$ is the intensity of the reconstructed 3D image, $O(x, y, z_d)$ is the number of overlaps at the reconstruction plane, E_{kl} is the kth column and lth row elemental image, c_x, c_y are the size of image sensor, x, y are index of pixels, Δx_s, Δy_s are the real-valued shifting pixels of each elemental image for 3D reconstruction, $\lceil \rfloor$ is the round operator, Δx_p, Δy_p are pixilated shifting pixels of Δx_s, Δy_s, respectively. As shown in Fig. 3, the shifting pixels between elemental images at any arbitrary reconstructed plane z_d are all the same and integer in conventional reconstruction method. Therefore, this computational volumetric reconstruction has worse depth resolution and reconstruction error.

3. Computational reconstruction of integral imaging with continuously non-uniform shifting pixels

In integral imaging system, the number of shifting pixels for each elemental image at any arbitrary reconstruction plane z_d is not uniform, because the actual value of shifting pixels is real value. However, in the computational volumetric reconstruction method, the accurate depth may not be estimated because the number of shifting pixels for all ele-