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Fast computational integral imaging reconstruction by combined use of spatial filtering and rearrangement of elemental image pixels

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ABSTRACT

In this paper, we propose a new fast computational integral imaging reconstruction (CIIR) scheme without the deterioration of the spatial filtering effect by combined use of spatial filtering and rearrangement of elemental image pixels. In the proposed scheme, the elemental image array (EIA) recorded by lenslet array is spatially filtered through the convolution of depth-dependent delta function array for a given depth. Then, the spatially filtered EIA is reconstructed as the 3D slice image using pixels of the elemental image rearrangement technique. Our scheme provides both the fast calculation with the same properties of the conventional CIIR and the improved visual quality of the reconstructed 3D slice image. To verify our scheme, we perform preliminary experiments and compare other techniques.

1. Introduction

Three-dimensional (3D) imaging and visualization using computational integral imaging technique has been widely studied for several applications including object recognition, tracking, encryption, and so on [1–9]. This computational integral imaging is composed of two stages: pickup and reconstruction. In pickup stage, an imaging device attached with a lenslet array captures perspectives of 3D objects into elemental image array (EIA). Then, the recorded EIA is used in the second computational integral imaging reconstruction (CIIR) stage which simulates the geometrical optics using the virtual pinhole model and generates a series of slice volumetric images. However, the slice images from CIIR suffer from low image quality due to the limitation of capture devices, unwanted granular noises, and magnification algorithm in superimposition of elemental images [10,11].

In the original CIIR stage, the magnification and superimposition processes can produce spatial filtering effect in the reconstructed slice images at a specific distance. However, this process may require a huge computational load to generate the slice image due to the copy operation of the magnified elemental images. If we consider the number of pixels to be processed and the number of operations per pixel, the CIIR stage has to deal with the $K^2 \times M^2 \times S^2$ pixels where each elemental image with S pixels is magnified using the copy operation by M times and K elemental images are repeated. For example, the operation number becomes 10^{10} pixels when $K=10$, $M=100$, and $S=100$ pixel. Compared with the typical 2D image processing where an image with 10^6 (1000×1000) pixels is processed, this is very huge and thus it prevents the real-time process for CIIR in the computational integral imaging.

To remedy these problems, some methods have been studied including interpolation and pixel rearrangement for elemental images [12–14]. They improved the calculation time by removing the copy operation in the magnification process by use of the pixel rearrangement [13] or fractional delay filter [4]. However, we lost the spatial filtering effect in the slice images. Like this, there is a tradeoff between calculation speed and spatial filtering effect.

In this paper, we propose a fast computation reconstruction method of the slice images without the deterioration of the spatial filtering effect. The proposed method is combined with both spatial filtering technique and rearrangement of elemental image pixels. First, the EIA recorded by lenslet array is spatially filtered through the convolution of depth-dependent delta function array for a given depth. Then, the spatially filtered EIA is reconstructed as the 3D slice image using pixels of the elemental image rearrangement technique. By doing so, we can obtain both the fast calculation time and the improved visual quality of the reconstructed 3D slice image even when the elemental images were distorted. To show the usefulness of the proposed method, we perform preliminary experiments and compare other techniques.

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2. Proposed method by combined use of spatial filtering and rearrangement of elemental image pixels

Before explaining the proposed CIIR, we present the principle of the overlapping process in CIIR. For illustration purpose, we assume a point source as the object. Typical integral imaging system with CIIR is shown in Fig. 1. In the pickup part as shown in Fig. 1(a), the rays coming from a point source are recorded through the lenslet array into the elemental images. Each elemental image has the different directions and intensity information of the 3D object. After the recording process, the elemental images are used in CIIR process which is implemented in computer. Here, the virtual pinhole array is used instead of the lenslet array to reconstruct 3D images. With the elemental images for the point source as shown in Fig. 1(b), the plane image is reconstructed at the original distance where the point source was located by properly back-propagating rays from elemental images. Then, we can reconstruct the point image by overlapping of inversely projected rays onto the reconstructed plane (z_I). The output pixel intensity of the point image in the reconstruction plane is calculated by the average value of all the integrated ray intensities.

To understand the effectiveness of the proposed method by combined use of spatial filtering and rearrangement of elemental image pixels, we first explain the convolution of depth-dependent delta function array. We consider the capturing process of elemental images by the direct pickup method based on ray optics. In the direct pickup method, the location of the pickup device may be considered for the imaging points of elemental images on the pickup sensor as shown in Fig. 1.

Considering that the rays are emitted from the point object to pass through the optical center of a pickup lens, the geometrical relation between a point object, its corresponding imaging points on the elemental image plane can be given by [15]

$$x_{En} = x_O + \frac{z_O}{z_O+f}\left[\left(n-\frac{1}{2}\right)P - x_O\right]. \tag{1}$$

In Fig. 1 and Eq. (1), the origin of the coordinate system is the edge of the elemental lens located at the bottom of the lens array. z_O and x_O represent the positions of the point object along the z and x axes, respectively. P represents the distance between the neighboring elemental lenses. f denotes the focal length of an elemental lens. In addition, x_{En} represents a point on the nth elemental lens, in which the valid x_{En} is restricted by $(n-1)P \le x_{En} \le nP$ in the direct pickup condition and n means the natural number.

From Eq. (1), one-dimensional form of the spatial period of the EIA depending on the object's depth can be given by $|x_{Es}-x_{E(s-1)}|$, where $2 \le s \le N$, and N is the number of lateral elemental lenses. Then, the spatial period depending on the object's depth can be calculated and given by [14]

$$X = \left|\frac{z_O P}{z_O+f}\right|. \tag{2}$$

Here, Eq. (1) indicates x coordinate of imaging point of a point object by each elemental lens as shown in Fig. 1. The imaging distance, z_E, of a point object measured from the lens array can be given by $z_E = z_O f/(z_O+f)$. The optical characteristics of an EIA in integral imaging method can be represented in terms of intensity impulse response and scaled object intensity by using the periodic property of an EIA depending on object's depth.

In conventional 2D imaging, when x_E represents the x coordinate on the EIA plane, $h(x_E)$ represents the intensity impulse response, and $f(x_E)$ represents the scaled object intensity while taking the image magnification into consideration, the image intensity can be calculated as $g(x_E) = h(x_E)^* f(x_E)$, where * denotes the convolution. For the 3D object, the image intensity can only be represented by $g(x_E)|z_O = f(x_E)|z_O{}^* h(x_E)|z_O$ having the z_O dependence because the intensity impulse response and the object intensity are dependent on object's depth z_O. Therefore, the z_O dependent image intensity is given by [16]

$$g(x_E) = \int h(z_O, x_E)^* f(z_O, x_E) dz_O. \tag{3}$$

Considering a continuously distributed intensity of 3D volumetric object, image intensity $g(x_E)$ represents summation of image intensity for continuously distributed space of object. If we assume the geometrical optics condition (wavelength $\lambda \to 0$), the intensity impulse response $h(z_O, x_E)$ may be represented by the δ-function. The intensity impulse response $h(z_O, x_E)$ in Eq. (3) represents the x coordinate on the imaging plane. Considering the periodic property of the imaging formation in lens array based integral imaging system, the intensity impulse response may be represented by summation of intensity impulse responses which is corresponding with each elemental lens. With Eqs. (1) and (2), the intensity impulse response $h(z_O, x_E)$ in Eq. (3) can be presented for an lens array system by $h(z_O, x_E) = \sum \delta(x_E - x_{E1} - nX)$, where x_{E1} and X are calculated from Eqs. (1) and (2), respectively. Therefore, the intensity impulse response can be given by

$$h(z_O, x_E) = \sum_{n=0}^{N-1} \delta\left(x_E - \frac{2x_O f + z_O P}{2(z_O+f)} - n\left|\frac{z_O P}{z_O+f}\right|\right). \tag{4}$$

As shown in Eq. (4), the intensity impulse response of the lens array system is considered as δ-function array whose spatial period varies depending on the depth of the object. Next, we

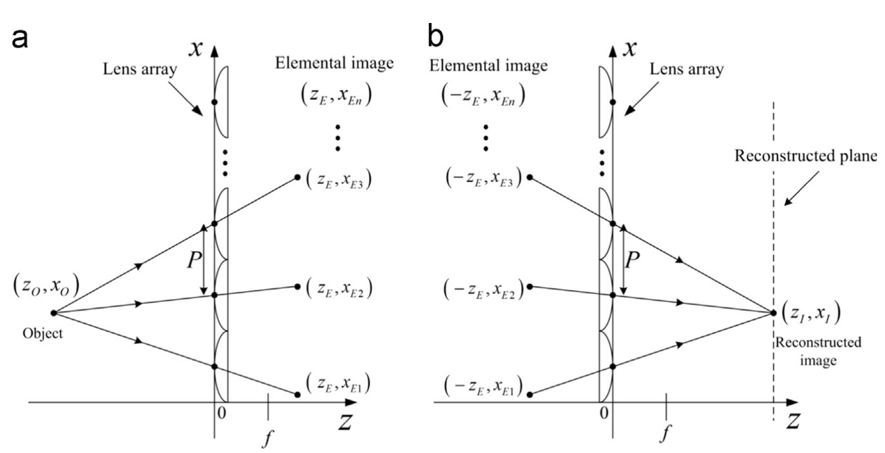

Fig. 1. Geometrical relation between a point object and its corresponding imaging points with a lens array (a) direct pickup (b) reconstruction.