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Improved 3-D image reconstruction using the convolution property of periodic functions in curved integral-imaging

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ABSTRACT

In this paper, we propose a new approach for image and depth resolution-enhanced reconstruction using the convolution property between elemental images and the periodic δ-function array in a curved integral-imaging system. For three-dimensional (3-D) image reconstruction based on the convolution property of periodic δ-functions, the image resolution is proportional to the number of sampling images to be convolved, and the depth resolution is inversely related to the focal length of the elemental-image pickup system. Thus, the use of a large aperture in the curved integral-imaging system allows us to enlarge the field-of-view of the pickup system and may improve the resolution and depth of the reconstructed images. To test the feasibility of the proposed method, experiments are performed with test objects, and the results are compared with the results of the conventional method in terms of resolution and depth. The experimental results indicate that the proposed method outperforms the conventional method.

1. Introduction

As an effective approach for three-dimensional (3-D) image reconstruction and visualization, integral-imaging has been extensively studied in various fields of application, including object recognition, depth extraction and object tracking [1–17].

Many different 3-D image reconstruction methods have been developed based on integral-imaging [4,5,17]. Arimoto and Javidi [4] proposed a computational method to reconstruct perspective images from picked-up elemental images. Hong et al. [5] presented the computational integral-imaging reconstruction (CIIR) method, which is based on the inverse ray-mapping of elemental images according to the distance of the reconstruction plane. This CIIR algorithm has been applied to various research fields [7–13]. That is, a CIIR-based depth extraction method was proposed to find the spatial locations of 3-D objects [7]. Several occlusion removal methods using the CIIR technique were also presented to improve the resolution of the reconstructed object images that were partially occluded by the pickup process [9,12,13]. Cho and Javidi also demonstrated the usefulness of the CIIR method in tracking a heavily occluded 3-D object [10].

Jang et al. proposed a new type of 3-D image reconstruction method based on an imaging property of the integral-imaging method [18]. In this method, the period of elemental images can be regarded as a function of object depth, focal length and the distance between the centers of neighboring lenses. Thus, using the correlation between the periodic δ-function array and the elemental images, we can extract the object depth corresponding to the specific period of the δ-function array. In this method, the reconstructed images can be obtained in an array format of depth-extracted images that are similar to the original elemental images. That is, the reconstructed images are composed of perspective images generated from many viewing angles. Therefore, these reconstructed images based on the convolution property of periodic functions (CPPF) might be very different from those generated by the conventional CIIR method, in which the reconstructed images are only generated along the center view.

In this CPPF-based 3-D reconstruction method, however, the image resolution is proportional to the number of sampling images to be convolved, and the depth resolution is inversely related to the focal length of the elemental-image pickup system. Moreover, in the conventional integral-imaging system using a planar lenslet array, the number of sampling images of the 3-D object in the elemental images is reduced according to its position, thus potentially creating unwanted image distortion in the 3-D reconstructed images.

Thus, to overcome this problem of the conventional CPPF, in this paper, the CPPF is applied to the curved integral-imaging system with a large aperture to reconstruct resolution and depth-enhanced 3-D images. The use of a large aperture in the curved

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integral-imaging system allows us to enlarge the field-of-view of the pickup system, thereby improving both image and depth resolution. Experiments are performed to demonstrate the effectiveness of the proposed scheme, and the results are compared to those of the conventional method.

2. 3-D image reconstruction with CPPF in conventional integral-imaging

Here, we review the CPPF-based 3-D image reconstruction method. The process of capturing elemental images by the direct pick-up method in the integral-imaging system is based on ray-optics. The geometric relationship between a point object and its corresponding point images on the elemental-image plane is shown in Fig. 1(a). In a conventional integral-imaging system with a planar lens array, the geometrical relationship can be given by

$$x_{Ek} = x_O + \frac{z_{On}}{z_{On}+f}\left[\left(k-\frac{1}{2}\right)P - x_O\right]. \tag{1}$$

In Fig. 1(a) 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_{On} and x_O represent the positions of the object points along the z and x axes, respectively. P also denotes the distance between the neighboring elemental lenses. Moreover, f represents the focal length of the elemental lens in the planar lens array, while x_{Ek} is the image point of the kth elemental lens.

As shown in Fig. 1(a), the imaging distance measured from the lens array z_{En}, $z_{En}=z_{On}f/(z_{On}+f)$, depends on z_{On} and f. From this geometric relationship, the spatial period depending on the object depth can be given as $|x_{Es}-x_{E(s-1)}|$, $2 \le s \le K$, where K is the number of lateral elemental lenses. Then, the depth-dependent period can be given by $|x_{Es}-x_{E(s-1)}| = |z_{On}P/(z_{On}+f)|$.

Because of the limited resolution of a pick-up device, however, the period units can be converted into pixel units. Thus, the period can be denoted by

$$X_{Z_{On}} = ceil\left[\left|x_{Es}-x_{E(s-1)}\right| \times \frac{\text{number of pixel}}{P \times \text{number of lens}}\right], \tag{2}$$

where the 'number of pixels' in Eq. (2) represents the lateral resolution of an elemental image in the one-dimensional (1-D) condition. Eq. (2) implies that the elemental image intensity corresponding to an object located at a specific depth can be imaged on the imaging plane with the same interval.

Using a depth-dependent periodic property, we can analyze the optical characteristics of the elemental image array in terms of intensity impulse response. Here, two-dimensional (2-D) image intensity can be written as $g(x_E)=f(x_E)*h(x_E)$, where $*$ and x_E denote the convolution and the x coordinate of the elemental image plane, respectively. $f(x_E)$ represents the scaled object intensity, which takes the image magnification into consideration, and $h(x_E)$ denotes the intensity impulse response [19]. Moreover, the depth-dependent image intensity of the 3-D object can be represented as $g(x_E)|_{z_{On}} = f(x_E)|_{z_{On}} * h(x_E)|_{z_{On}}$.

Assuming the geometrical optics condition ($\lambda \to 0$), the intensity impulse response $h(x_E)|_{z_{On}}$ can be represented by the δ-function. Thus, in the integral-imaging system with a planar lens array, the 1-D description of the elemental image intensity corresponding to

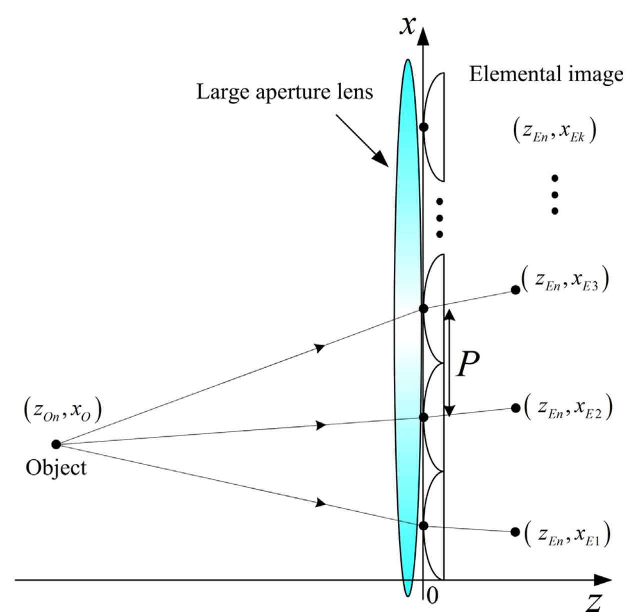

Fig. 2. Geometric correspondence in the curved integral-imaging system.

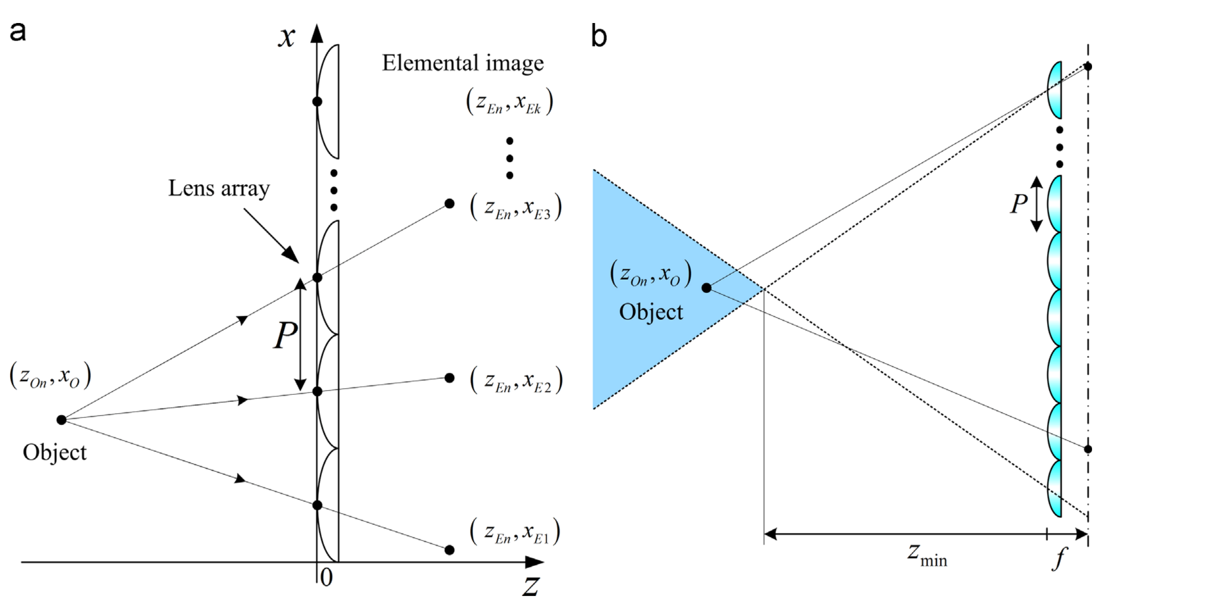

Fig. 1. (a) Geometric relationship between a point object and imaging points in the conventional integral-imaging system with a planar lens array; (b) effective viewing zone.