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Perspective-variant reconstruction of a three-dimensional object along the depth direction with virtually generated elemental images by ray-based pixel mapping in integral-imaging

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ABSTRACT

In this paper, we propose a novel approach to reconstruct the perspective-variant three-dimensional (3-D) objects along the depth direction with virtually generated elemental image arrays (V-EIAs) by ray-based pixel mapping in integral-imaging. In the proposed method, V-EIAs having different perspectives of a 3-D object are generated from the originally picked-up EIA (O-EIA) on a specific depth point by virtually moving the pinhole array back and forth along the depth direction of the 3-D object, and mapping each pixel of the O-EIA on to the corresponding positions of the V-EIAs based on ray-optics. With these V-EIAs, perspective-variant 3-D objects are finally reconstructed along the depth direction of the 3-D object. To confirm the feasibility of the proposed method, experiments with test 3-D objects are performed and the results are discussed.

1. Introduction

Basically, the elemental image array (EIA) or elemental images (EIs) of a three-dimensional (3-D) object, which are picked up on a specific depth point in the conventional integral-imaging system, have their own perspective information of a 3-D object. Only the 3-D object image viewed on that pickup point could be reconstructed from this captured EIA. This is because the object's perspective is fixed by the camera's pickup point at which the EIA of the 3-D object was captured [1–5].

Even though the 3-D object can be reconstructed in a magnified or de-magnified form when the EIA was captured by using the zoom-in or zoom-out operation of the camera system at a fixed pickup point, all these scaled object images, however, have the same viewpoints due to the fact that all of the rays coming from the 3-D object were the same on that pickup point [6].

The viewpoint of a 3-D object can be changed as the pickup camera moves closer to the object or moves away from it along the depth direction of the 3-D object. That is, the viewpoint of the 3-D object may depend on the relative distance between the camera's pickup point and the 3-D object [6]. Consequently, in order to reconstruct the 3-D objects that have different perspectives, multiple EIAs of a 3-D object have to be picked up by physically moving the camera system to the corresponding depth points. However, to pick up as many EIAs of the 3-D object as required in the real applications seems to be time-consuming and impractical.

Therefore, it would be very useful if the perspective-variant 3-D object images can be reconstructed along the depth direction with a very limited number of EIAs captured on the specific pickup points.

Thus far, several methods for a scalable reconstruction of the 3-D object images in the conventional integral-imaging system have been suggested [7–14]. One of them is the method based on the repositioning and scaling of picked-up EIs to reconstruct the scaled 3-D object images [7–10]. Another method is the one based on the depth map extracted from the picked-up EIs, with which the scaled EIs for reconstruction of the 3-D object image were generated [11–14].

Furthermore, a moving-array-lenslet-technique (MALT) was presented for picking up many time-multiplexed EIAs instead of modification of the picked-up EIs [15,16]. In this method, the scalability could be achieved by controlling the spatial sampling rate. In addition, an intermediate-view-reconstruction-technique (IVRT) was also proposed [9,12], in which a number of intermediate EIs, as many as required can be computationally synthesized by using the limited number of picked-up EIs.

Even though these scalable integral-imaging systems have shown a reasonable performance in reconstruction of the magnified or de-magnified 3-D object image, these approaches, however,

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could obtain only the scaled 3-D objects without any variations of viewpoints because the object's perspective is fixed by the pickup point of the EIs regardless of the object scaling in the reconstruction process.

Meanwhile, in the field of light-field photography [17,18], an approach to digitally alter the perspective and viewpoint of the scene has been presented. In this method, a light-field camera was employed for capturing the directional lighting distribution of the scene arriving at each location on the sensor. Then, it has been demonstrated that with these acquired light fields, photographs as if taken with a synthetic conventional camera that were positioned and focused differently than the acquisition camera could be computed.

Recently, in the field of integral-imaging, a computational method to reconstruct a free-view of a partially occluded 3-D object by using the integral-imaging technique has been proposed [19]. In this method, off-centered view EIAs of a 3-D object are generated from the center view EIA, which has been picked-up at a fixed depth point, by employing the self-rotatable integral-imaging system (SRIIS). However, with this method, only the angularly different views of a 3-D object at a fixed depth point could be reconstructed.

Accordingly, in this paper, we propose a novel approach to reconstruct the perspective-variant 3-D objects along the depth direction with virtually generated elemental image arrays (V-EIAs) by using the ray-based pixel mapping method in the conventional integral-imaging system. In the proposed method, the V-EIAs having different viewpoints of a 3-D object are generated from the originally picked-up EIA (O-EIA) on a specific depth point by virtually moving the pinhole array back and forth along the depth direction of the 3-D object, and mapping each pixel of the O-EIA on to the corresponding positions of the V-EIAs based on ray-optics [20].

Here, the V-EIAs may act just like the EIAs virtually captured on the different depth points during the pickup process. Therefore, from these V-EIAs, various depth-dependent 3-D objects having their own perspectives can be reconstructed. To confirm the feasibility of the proposed method, experiments with test 3-D objects are performed and the results are discussed.

2. Scale and perspective variation of a 3-D object according to the depth direction

The scale and perspective variations of a 3-D object can be analyzed by using two types of camera pickup process [6]. One is the case in which many different 3-D object images are captured at a fixed pickup point just by varying the focal length of the camera system. In this case, all picked-up object images may be scaled in size depending on the camera's focal length. However, they all have the same perspectives of the 3-D object since all directions of the rays originating from a 3-D object are exactly the same as each other on that fixed pickup point.

The other is the case in which many different 3-D object images are captured by changing the camera pickup points along the depth direction of the 3-D object. In this case, we can obtain various 3-D object images varying in perspectives depending on the physical pickup points of the camera system.

As shown in Fig. 1, the scale and perspective variation of the 3-D objects depending on the pickup point and the focal length of the camera system can be explained by using the field-of-view of the perspective plane. That is, Fig. 1(a) and (b) shows the object images picked up on the same depth point of z_1 with two kinds of camera lens systems having the focal lengths of f_1 and f_2 ($f_2 > f_1$), respectively, whereas the object images of Fig. 1(c) are captured on the shorter depth point of z_2 ($=z_1$–d) than z_1 with the camera lens system having the focal length of f_1.

As seen in Fig. 1, the viewing-angle θ_2 of the 3-D objects shown in Fig. 1(c) is much larger than the viewing-angle θ_1 of Fig. 1(a) because the pickup camera of Fig. 1(c) is situated closer to the objects than the case of Fig. 1(a). Accordingly, the perspective and scale of the objects of Fig. 1(c) look different from those of Fig. 1(a). In other words, Fig. 1(c) shows the magnified object images having a different perspective compared to Fig. 1(a). In particular, differences in the gaps between the ‘White dice’ and the ‘White sphere’ and between the ‘White sphere’ and the ‘Brown dice’ can be clearly recognized. That is, the gaps between three objects in Fig. 1(c) get much closer than those of Fig. 1(a) due to the perspective variation of the 3-D objects.

On the other hand, the viewing-angle θ_1 of Fig. 1(a) is the same as that of Fig. 1(b) because they were picked up at the same depth point of z_1, which means their perspectives of the objects are the same as each other. However, the object images of Fig. 1(b) are magnified in size because they were captured by using the camera lens system having a longer focal length of f_2 than f_1 of Fig. 1(a). Here, the object images of Fig. 1(b) can be viewed as the zoomed-in version of Fig. 1(a). In other words, there are no changes in perspective between the object images of Fig. 1(a) and (b) even though the object images of Fig. 1(b) are reconstructed to be magnified in size. Thus, the results of Fig. 1 confirm that the perspective of the reconstructed 3-D object image can be determined by the camera pickup point. Therefore, for reconstruction of the depth-dependent 3-D object images, multiple EIAs must be picked up by changing the camera pickup points.

3. Proposed ray-based pixel mapping method

3.1. Geometric structure of the proposed method

Actually, a 3-D object can be modeled as a collection of point sources, in which rays emanating from each point source pass through the pinhole centers, and are recorded as the pixels on the EIs plane in the pickup process of the conventional integral-imaging system [5,9,13]. Here, it is assumed that there exists one-to-one correspondence between the point sources of a 3-D object and the recorded pixels on the picked-up EIs through the pinhole array, and the pinhole array can be virtually moved back and forth along the depth direction while keeping a parallelism between the virtually moved pinhole arrays and the original pinhole array. Then, many other V-EIAs having different viewpoints can be computationally generated from the originally picked-up EIA on a specific depth point by using the proposed ray-based pixel mapping method.

Fig. 2 shows a geometric structure of the proposed ray-based pixel mapping method. The original and two virtual pinhole arrays are assumed to be located at $z=0$ and $z=\pm\Delta z$, respectively, then two kinds of V-EIAs, the near-field and the far-field virtual EIA, may be generated. Here, in this paper, only the near-field case is considered because the same procedure can be applied to the far-field case, and the y-coordinate is also omitted in Fig. 2 for simplicity.

Several parameters can be defined here in Fig. 2 for geometric analysis of the proposed method. That is, g means the gap between the pinhole plane and the EIA plane, and Δz represents the moving distance from the original pinhole array to the virtual pinhole array along the depth direction. In addition, the pixel coordinates of x, y and x', y' represent the distances dislocated from the vertical lines drawn at each pinhole center of the