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Refocusing-range and image-quality enhanced optical reconstruction of 3-D objects from integral images using a principal periodic δ-function array

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A B S T R A C T

We propose a method for refocusing-range and image-quality enhanced optical reconstruction of three-dimensional (3-D) objects from integral images only by using a 3×3 periodic δ-function array (PDFA), which is called a principal PDFA (P-PDFA). By directly convolving the elemental image array (EIA) captured from 3-D objects with the P-PDFAs whose spatial periods correspond to each object's depth, a set of spatially-filtered EIAs (SF-EIAs) are extracted, and from which 3-D objects can be reconstructed to be refocused on their real depth. convolutional operations are performed directly on each of the minimum 3×3 EIs of the picked-up EIA, the capturing and refocused-depth ranges of 3-D objects can be greatly enhanced, as well as 3-D objects much improved in image quality can be reconstructed without any preprocessing operations. Through ray-optical analysis and optical experiments with actual 3-D objects, the feasibility of the proposed method has been confirmed.

1. Introduction

Thus far, optical three-dimensional (3-D) refocusing based on integral imaging has attracted many attentions in various application fields such as 3-D biomedical imaging, 3-D target recognition, spatial interfacing and interaction, and 3-D photography since it may allow the refocused reconstruction of 3-D object images on their real depth from elemental images (EIs), which are picked up from 3-D objects through lens arrays, as well as it can provide various perspective views of the 3-D objects at different viewing directions [1–5].

In the integral imaging system [6–22], a set of two-dimensional (2-D) object images with different perspectives of 3-D objects are captured as a form of elemental image array (EIA) on the CCD camera through a lens array. Several other capturing methods such as synthetic aperture integral imaging (SAII), axially-distributed sensing (ADS), and off-axially distributed image sensing (ODIS) techniques have been also proposed [11–13]. From this picked-up EIA, 3-D objects can be digitally or optically reconstructed. For the digital reconstruction, various computational integral-imaging reconstruction (CIIR) algorithms have been used [14–20]. In this CIIR-based method, however, 3-D objects can be reconstructed as a set of discretely-sliced 2-D plane object images (POIs). On the other hand, in the optical reconstruction, all those 3-D objects with different depth are simultaneously reconstructed from the captured EIA in space by combined use of the display panel and lens array [21–23]. In other words, each 3-D object cannot be separately reconstructed to be refocused on its depth since the information of input 3-D objects is mixed up together in the captured EIA.

Thus, for the optical refocusing of 3-D objects, a scheme to selectively extract the object data only related to each depth from the captured EIA is needed. Recently, a periodic δ-function array (PDFA)-based optical 3-D refocusing method was proposed, where depth-dependent spatial-filtering of the captured EIA can be carried out based on a sifting property of the PDFA [24]. In fact, there exists a geometrical correspondence between each object depth and the spatial period of the corresponding object image captured on the EI plane through the lens array [24]. Thus, by convolving the captured EIA with PDFAs whose spatial periods correspond to each object depth, a set of EIA data only related to their depth can be selectively sifted out from the captured EIA, which is called spatially-filtered EIAs (SF-EIAs). From these SF-EIAs, each 3-D object can be reconstructed to be refocused on their real depth. Here in this method, PDFA sizes are made to be same with that of the captured EIA even though they have different spatial periods depending on the object depth, thus it is called the global PDFA (G-PDFA) here.

The G-PDFA-based 3-D refocusing method, however, has a critical problem that it works only for the 3-D objects locating within a specific pickup range, which is known as the effective-capturing-zone

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(ECZ) [24–27]. In case 3-D objects are located beyond the ECZ, those objects cannot be seen by all components of the lens array, which means that each object data can be contained in the limited number of EIs on the captured EIA. Thus, when this EIA is convolved with the G-PDFA whose spatial period corresponds to a specific depth, not only the EIA data related to that depth, but also its many laterally-shifted versions, are simultaneously extracted due to the shifting and adding operational property of the G-PDFA-based convolution integral. It thus results in a severe distortion of the reconstructed object image. To overcome this ECZ problem, this method tried to perform the G-PDFA-based convolution operations on the sub-image array (SIA) plane being transformed from the picked-up EIA plane and showed some experimental results [24]. But, the detailed performance analysis of this approach in terms of the ECZ was not provided. Moreover, this method requires additional image processing such as EIA-to-SIA and SIA-to-EIA transformations.

For solving this drawback, another optical 3-D refocusing method based on subdivided-elemental image arrays (sub-EIAs) and local periodic δ-function arrays (L-PDFAs) was proposed [27]. In this method, the captured EIA from 3-D objects is divided into a number of sub-EIAs depending on the object distance from the lens array, which allows the object data for each depth to be contained in the limited number of sub-EIAs. Thus, by convolving those sub-EIAs with L-PDFAs whose spatial periods corresponds to each object's depth, as well as whose sizes are exactly matched to that of the corresponding sub-EIA, arrays of spatially-filtered sub-EIAs (SF-sub-EIAs) for each object depth can be uniquely extracted. Here, the ECZ of this L-PDFA-based method can be somewhat extended because the ECZ of this method can be given by the summation of all sub-ECZs corresponding to each sub-EIA. In other words, even a 3-D object located much close to the lens array can be refocused on its real depth without any laterally-shifted versions since the cropping process prevents the L-PDFA from making image duplications on other sub-EIAs.

This method, however, requires a couple of preprocesses such as extraction of the object depth for determining the sizes of sub-EIA and L-PDFA, and cropping of the picked-up EIA into an array of sub-EIAs. Each sub-EIA is then spatially filtered with the L-PDFA, and from which an array of SF-sub-EIAs can be generated. In addition, this method also suffers from the low image-quality of the reconstructed 3-D object image since those SF-sub-EIAs show gradual changes in intensity due to the locally different times of superposition operations of sub-EIAs. That is, each center area of the SF-sub-EIAs shows the highest brightness since the maximum number of superposition operations of sub-EIAs is performed there, whereas other areas show gradual reductions of their intensities as being moved away from the center location due to their less numbers of superposition operations of sub-EIAs. This non-uniformity in intensity distribution of SF-sub-EIAs causes the image quality of the reconstructed 3-D object to be much deteriorated. Furthermore, since all those sub-EIAs must be made same in size, the minimum number of EIs in each sub-EIA is limited by the number of the lens array, which causes the corresponding sub-ECZ range to be decreased, leading to the reduction of the total ECZ range of the system.

Accordingly, in this paper, we propose a new method to capture 3-D objects in an input scene, and reconstruct them to be refocused on their depth with practically no limitations of pickup and depth ranges, as well as much enhanced in image quality only by using a single 3×3 PDFA [27]. Here, a 3×3 PDFA can be regarded as the smallest PDFA in size for its practical sifting operation, thus it is called here a principal PDFA (P-PDFA).

In the proposed method, just by directly convolving the EIA captured from the 3-D objects with the P-PDFAs whose spatial periods correspond to each object's depth, a set of SF-EIAs are extracted, and from which 3-D objects can be optically reconstructed to be refocused on their real depth on the space. Here, the ECZ range of the proposed system can be maximized since each minimum number of 3×3 EIs of the picked-up EIA is convolved with the P-PDFA. Thus, the proposed method can cover significantly enhanced depth ranges of the 3-D objects in the pickup and reconstruction processes, which means that 3-D objects can be captured and reconstructed to be refocused on their real depth on the practically-maximized ranges of depth. Moreover, in the proposed system, a couple of preprocessing operations such as depth extraction and image cropping may not be required, which results in an image quality-enhanced reconstruction of 3-D objects.

To confirm the feasibility of the proposed method, ray-optical analysis and optical experiments with actual 3-D objects are carried out, and the results are comparatively discussed with those of the conventional methods.

2. Operational principle of the PDFA-based 3-D refocusing

In fact, the operational principle of the PDFA-based 3-D refocusing method is rooted on the object depth-dependent spatial-filtering property of the periodic δ-function array (PDFA) [24,26,27]. In the lens array-based integral imaging system, 3-D information of an object is captured as the 2-D EIA by combined use of the lens array and CCD camera. As seen in Fig. 1, in this system, a geometrical correspondence between the object depth and the spatial period of the corresponding object images captured on the EI plane through the lens array, must exist. In other words, the spatial period of the object images picked up on the EIA is given by a function of the object depth. Thus, the object data only related to a specific depth, which is called spatially-filtered EIA (SF-EIA), can be extracted just by carrying out the convolutional integration of the captured EIA with the PDFA whose spatial period corresponds to that depth. From this SF-EIA, only the object with the corresponding depth is reconstructed to be refocused on its real depth. From Fig. 1, the geometrical relationship between a point object locating at the depth plane of (z_{Om}, x_{Om}) and its corresponding point images captured on the EIs of x_{Ej} can be given by Eq. (1) [24,26,27].

$$x_{Ej} = x_{Om} + \frac{z_{Om}}{z_{Om} + f}[(j - \frac{1}{2})P - x_{Om}] \tag{1}$$

Where the origin of the coordinate system is set to be the edge of the lens located at the bottom of the lens array, and x_{Ej} denotes the point image passing through the jth elemental lens. In addition, z_{Om} and x_{Om} represent the positions of the object point along the x and z-axes, and P and f also represent the pitch of a lens array and the focal length of each elemental lens of the lens array, respectively. Now, the imaging distance of a point object passing through each elemental lens, z_{Em} can be given by Eq. (2) based on the thin-lens equation [24,26,27].

$$z_{Em} = \frac{z_{Om} f}{\left(z_{Om} + f\right)} \tag{2}$$

Eq. (2) tells us that the imaging distance of a point object depends on the object depth and the focal length of the elemental lens. That is, it shows the relationship between the object distance and imaging distance.

Since the EIA is captured on the CCD sensor with a limited pixel number, the unit of the period of x_{Ej} must be converted into that of the pixel. Thus, the pixelated version of Eq. (1) X_{CEj} can be given by Eq. (3).

$$X_{CEj} = ceil\left[\frac{x_{Ej} N}{PK}\right] \tag{3}$$

In Eq. (3), N and K represent the pixel number of the EIA and the number of elemental lens along the lateral x-direction, respectively.

From the geometrical relationship between a point object and its point images as shown in Fig. 1, the spatial period of the point images on the EIA, which depends on the object's depth, can be derived by Eq. (4).

$$\left|x_{Ej} - x_{E(j-1)}\right| = \left|\frac{z_{om}}{z_{om} + f} P\right| \tag{4}$$

Where $2 \le j \le K$, and K represents the number of elemental lenses of the lens array along the x-direction as mentioned above. Since the