Digital Magnification of Three-Dimensional Integral Images

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***Abstract*—The methods for obtaining a controlled magnification of three-dimensional (3-D) integral images are usually based on the increase of the spatial ray-sampling rate of elemental image arrays. This is usually done by use of the moving array-lenslet technique. The major drawback of this technique is the alignment complexity due to the small lenslet movement. In this paper, we are proposing a digital magnification method that uses interpolation principles to increase the spatial ray sampling rate of elemental image arrays without lenslet movement in the pickup procedure. We compare the reconstructed 3-D integral images obtained when using the optical or the digital magnification methods, and show that the quality of both reconstructed 3-D integral images is the same.**

***Index Terms*—Image size analysis, integral imaging, integral photography, interpolation, three-dimensional (3-D) imaging.**

I. Introduction

MODERN digital technology is constantly developing, so that better image systems for acquisition and display procedures can be implemented. Nowadays a cellular phone or personal data assistant has the possibility of picking up and displaying digital two-dimensional (2-D) images in seconds and with good quality. This development is also supporting the study of 3-D images as holography, integral imaging and stereoscopic images. The so-called Integral Imaging (II), first proposed by Lippmann [1] in 1908, has been studied in the last couple of decades using the new technology of sensor and display devices. The renewed II has been proposed as a real solution to display 3-D images which includes 3-D TV [2]–[4]. Compared with other 3-D systems, II presents advantages such as continuous view points, full parallax, no special eyewear devices for users are needed, and there is no convergence-accommodation conflict.

The II system records a 3-D object using a microlens array, which produces an array of 2-D elemental images over a CCD sensor. Each elemental image contains a particular perspective of the object. To reconstruct a true 3-D image the elemental image array is displayed in a liquid crystal display (LCD) in front of a microlens array or the so-called projection type II that projects the elemental image array over a micro convex-mirror array [5]. The reconstruction stage converges, or diverges, the rays from each elemental image. The conventional pickup procedure is shown in Fig. 1(a) and the display procedure for projection type II is shown in Fig. 1(b).

Many studies have been performed in order to solve the resolution limitation of II [6]–[10], increase depth of focus [11]–[13], and many other analysis and challenges in II [14]–[17], because of the interest of improving 3-D image quality. Recently, the scaling problem in 3-D II was studied and solved by increasing (or decreasing) the spatial ray sampling rate of elemental image arrays in the pickup procedure [18]. Hereon, we call this technique the optical magnification (OM) method. In the first stage of OM method, an adequate number of sets of elemental-image arrays are picked up with a moving array lenslet technique (MALT) [9]. The elemental-image arrays are cut into separate elemental images and rearranged into a single elemental-image array. The new elemental-image array contains more elemental images than the original array. Therefore, the spatial ray-sampling rate of the original elemental image array is increased. The 3-D-scaled image is reconstructed by displaying the new elemental image array through a stationary lenslet array.

The need for picking up a high number of elemental-image arrays makes the OM technique very complex. The number of arrays increases as the square of the magnification factor. A major problem of OM is the alignment of elemental images due to the cut and rearrangement procedure. In this paper, we proposed to reduce the complexity and alignment problem using digital magnification (DM) processing.

Digital image magnification has been performed in 2-D images since the beginning of computer graphics and image processing [19], where simple interpolation algorithms were applied to display larger images and re-sample digital images using nearest neighbor or linear interpolation [20]. Nowadays 2-D digital magnification is more popular than optical magnification because of its simplicity.

We follow the basic principle of 2-D DM that estimates unknown pixel values from known values. Then we can calculate the new elemental images required to over-sample the array using original elemental images. This means that we can increase the spatial ray sampling rate of the elemental image array without lens movement. However, blurred 3-D integral images

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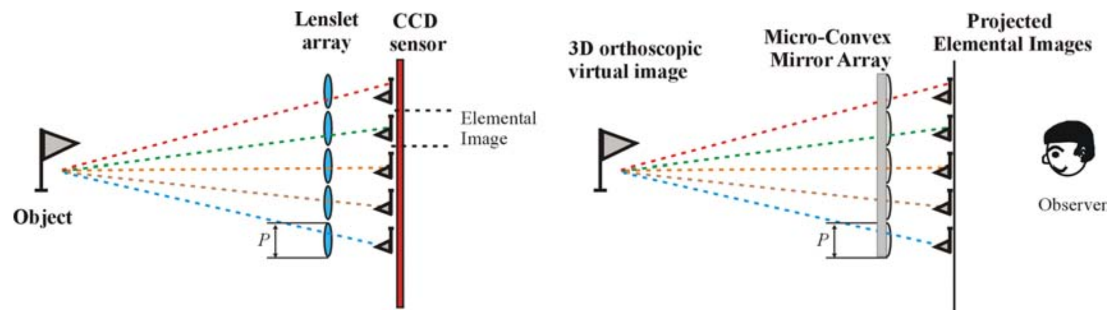

(a) (b)

Fig. 1. Pickup and display in 3-D II. (a) The pickup procedure of II. (b) The display procedure using 3-D projection II with a micro-convex mirror array or a lenslet array with low reflectivity. 2-D image projectors are not shown. (Color version available online at http://ieeexplore.ieee.org.)

could be reconstructed if one would not consider that the new elemental images must contain direction information of the 3-D object. A simple ray sampling analysis of the pickup procedure provides the rule to make new elemental images with intensity and correct direction information for a good 3-D reconstruction.

Our experimental results help us to show that 3-D integral images reconstructed by use of the DM method have the similar quality, seen by naked eye, as the ones reconstructed by the OM method, even though we appreciate resolution problems. Besides, we find that one can digitally magnify an object with fewer elemental-image arrays and the error due to misalignment in the optical magnification OM method is avoided.

This paper is organized as follows. In Section II we give an overview of the optical magnification method. In Section III we explain the digital magnification method. Experimental setup and results are shown in Section IV and finally conclusions and remarks of our work are presented in Section V.

II. OM Method

A. Principles of Integral Imaging

As explained in the previous section, an II system records on a charge-coupled device (CCD), through a micro-lenslet array, the direction and intensity information of a 3-D object, as shown in Fig. 1(a). In the display stage, the real (or virtual) 3-D integral image is reconstructed by converging (or diverging) rays from the elemental images. As shown in Fig. 1(b), the elemental-image array can be projected through a micro-convex-mirror array [5] and reconstructs a 3-D orthoscopic virtual image. The pick up lenslet array can be used as a micro-covex mirror with low reflectivity assuring the same pitch and focal length as in the pickup stage. The reasons for using projection type II in the display procedure are that the viewing angle is very wide (about 60 $\sim$ 70 deg) and pseudoscopic to orthoscopic image conversion is not needed.

B. Principles of the OM Method

Some studies have been performed concerning the scaling of 3-D integral images [8], [21], [22]. The OM method proposed by Song *et al.* [18], is based on the control of the spatial ray-sampling rate of an elemental image array in the pickup procedure.

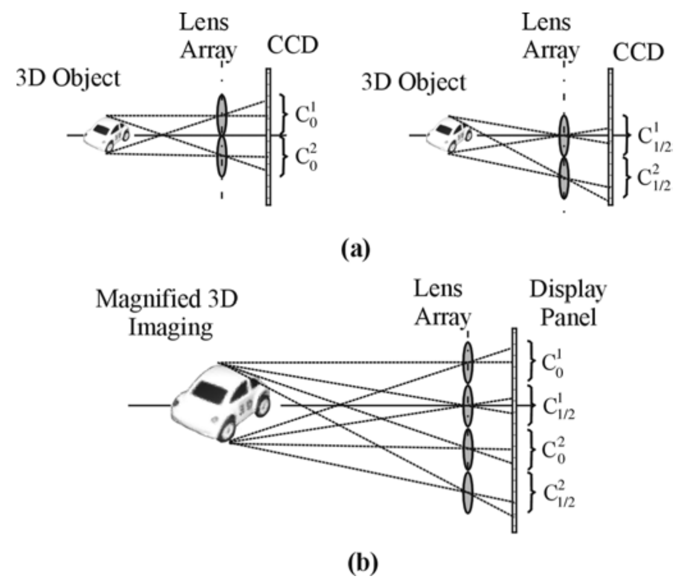

Fig. 2. Principle of the OM method. (a) Pickup procedure of the OM method using a MALT. (b) Display procedure of the OM method using a stationary lenslet array.

This technique enlarges 3-D II by increasing the spatial ray-sampling rate, which is performed by decreasing the pitch of the pickup lenslet array.

The OM technique is divided into three stages: the pickup, the digital rearrangement and the display procedure. In Fig. 2, the OM technique is schematized for one lateral dimension magnification.

In this first stage, a pickup procedure based on MALT samples a 3-D object in various elemental-image arrays at a time using a lateral movement of the lenslet array. This interval movement has an inverse relation with magnification factor m as a fraction of lens pitch p in an array, given by p/m. The number of elemental image arrays obtained by this method has a quadratic relation with magnification factor m, so that the final result of the pickup procedure is a set of m^2 elemental-image arrays.

In the example of Fig. 3, we assume a 2×2 lenslet array that produces the same number of elemental images. For a magnification factor of two, four elemental-image arrays $C_{i,j}$ must be

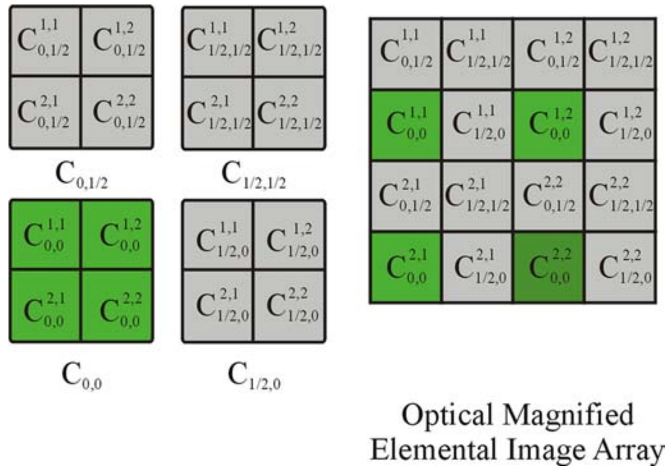

Fig. 3. Optical magnification produces over-sampled elemental image array using MALT and rearrange the elemental images in a single array that produce a 3-D magnified reconstructed II image. (Color version available online at http://ieeexplore.ieee.org.)

picked up by MALT at four sampling points (i,j), where i and j are fraction of the lens pitch.

In the second stage, the set of recorded elemental-image arrays are cut apart into single elemental images. We denote an elemental image as $c_{i,j}^{k,l}$, where (k,l) is the position of the elemental image inside of a (i,j) array. The set of cut elemental images is arranged in an array as if they were picked up in a single shot using a lenslet array with half pitch. The output of this procedure is a single elemental-image array that is called an over-sampled array because it contains all the picked up elemental images.

The final stage displays this single elemental-image array through an optical reconstruction system for II, but using more lenslets than in the pickup process. A magnified 3-D reconstructed integral image is thus generated. Thus, in the 3-D reconstruction stage of the example in Fig. 3, 4×4 elements of the reconstruction setup are used. A magnified 3-D integral image is reconstructed at a distance, from the lenslet plane, larger than in the original 3-D integral image [8], as is show in Fig. 2(b).

The complexity of the OM method will increase sharply according to a magnification factor m. The complexity is related with the mechanical nature of MALT and the small interval of lenslet array movement.

C. Lateral and Longitudinal Magnification

The magnification factor m provided by this technique is the same in depth and transverse directions, so a true magnification of the 3-D object is achieved.

Let us consider two object points A and B at different distances in longitudinal direction $z$as is show in Fig. 4(a). Object A is recorded by two adjacent elemental images, each one contains a location of object point. We define the distance between the images of an object point A provided by neighbor micro-lenses w_A as

$$w_A = p + \frac{pf}{d_A} \tag{1}$$

where p is the pitch of the lenslet array or distance between the center of each lenslet, f is the focal length of lenslets, and d_A is the gap distance between the pickup lenslet array and point A. The distance w_A gives direction information from object point A on the recording plane. Now, in the OM technique we change the distance p in the pickup setup to p' in the display setup as is shown in Fig. 4(a) and (b). Following the geometrical consideration that yields (1), we have:

$$w'_A = p' + \frac{p'f}{d'_A} \tag{2}$$

where w'_A denotes the new distance between the point images of A, A'_i and A'_{i-1}, in the two adjacent elemental images, and a' is the location of the reconstructed point A'. As the location of the recorded point A inside the two elemental images is the same in the recorded setup and in the display set up, we have

$$w_A - p = w'_A - p' \tag{3}$$

and we find the relation:

$$\frac{p'}{p} = \frac{d'_A}{d_A}. \tag{4}$$

Similar equations to (1)–(3) can be obtained for object point B considering the depth difference b then (4) is rewritten as

$$\frac{p'}{p} = \frac{d'_A + b'}{d_A + b}. \tag{5}$$

From this equation we find the longitudinal or depth magnification as

$$\frac{b'}{b} = \frac{p'}{p} = \frac{d'_A}{d_A}. \tag{6}$$

The lateral separation between objects A and B defined by a is magnified to a new value a'. The lateral magnification can be related with longitudinal magnification using (5) and the similarity between the triangles ABC and $A'B'C'$. We define lateral magnification as

$$\frac{a'}{a} = \frac{d'_A + b'}{d_A + b} = \frac{p'}{p}. \tag{7}$$

The equality of lateral magnification and longitudinal magnification is obtained.

III. DM Method

A. Principles of 3-D DM

The scaling of 3-D integral images can be done by OM as described above. However, the OM requires the MALT in the pickup stage. Here we propose a technique, the DM, which overcomes the scaling problem without MALT technique. In DM,

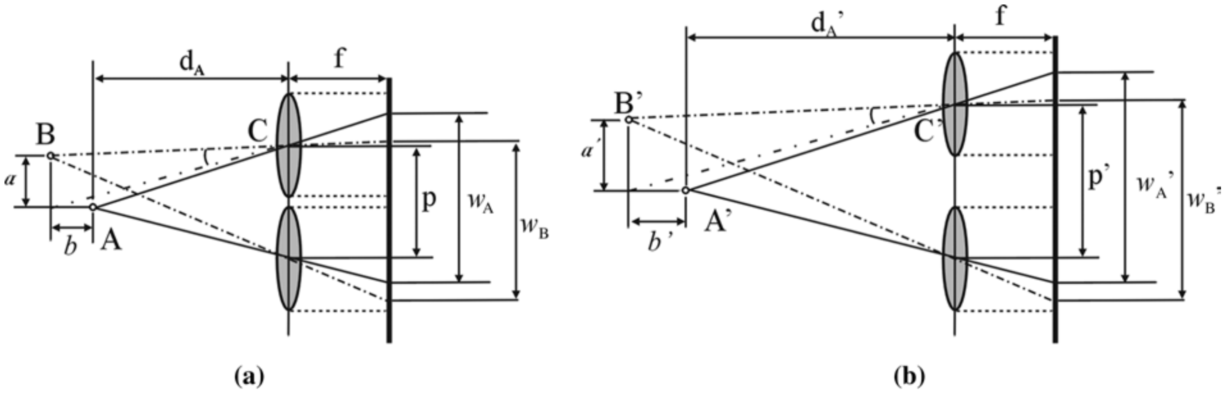

Fig. 4. Longitudinal and transversal magnification by controlling spatial ray sampling rate. The object consists of two points A and B. The lateral distance between the points is a and the longitudinal is b. (a) Pickup with sampling rate $1/p$. (b) Display with sampling rate $1/p'$.

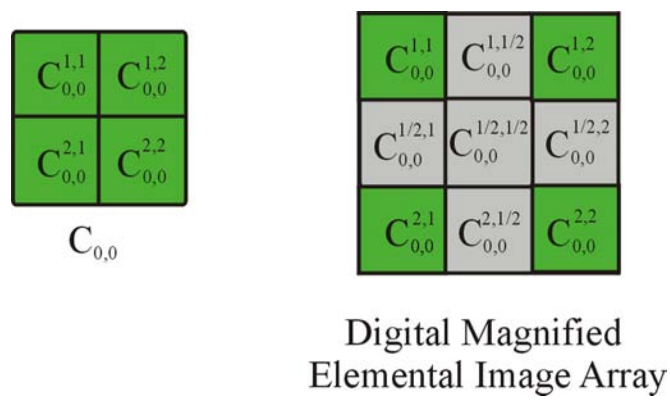

Fig. 5. The digital magnification algorithm uses a single elemental image to calculate the over sampled elemental images. Each square is an elemental image and fractional numbers represent elemental images calculated digitally. (Color version available online at http://ieeexpore.ieee.org.)

the additional elemental images needed for the scaling are generated by digital processing.

So the DM technique is divided into three stages: the pickup, the digital processing and the display procedure. In the pickup stage, the elemental images are recorded in a conventional II system. A single elemental image array is recorded. In the digital processing stage, new elemental images must be generated. In the beginning of digital image processing, the simple magnification of 2-D images was proposed with simple interpolation algorithms using nearest neighbor or linear interpolation [20]. The basic idea is to re-sample the original digital image interlacing new pixels between the already known.

The nearest neighbor algorithm replicates a pixel in the x and y direction, while the linear (or bilinear for 2-D function) interpolation calculates a new pixel by averaging two neighboring pixels, first in the x direction and second in the y direction [23], [24]. The final magnified 2-D image has more pixels than the original one.

In the case of the 3-D integral image scaling, we can magnify the array by digital calculation of new elemental images to be interlaced.

Nikolaidis *et al.* have proposed algorithms for calculation of new images in a stereoscopic system for 3-D image processing [25]. These algorithms consider the depth information inside of each 2-D image of the system.

For the purpose of our work, we use a simple technique that follows the basis of interpolation algorithms. New elemental images are calculated by replication of elemental images, or average between neighbors.

Although there are more elaborated approaches to the interpolation problem, the simplest one has some interesting advantages. On one hand, it requires low-time consuming processing and low access memory as much as in a personal computer (which is mandatory in real-time imaging and TV). On the other hand, the low resolution of elemental images and the display system makes unnecessary the use of more complex algorithms.

Fig. 5 shows the magnification scheme of the DM method. The DM method uses only one elemental image array $C_{0,0}$ pick up by a lenslet array in position (0,0). The gray elemental images labeled with fractional numbers in Fig. 5 are generated by using interpolation principles between adjacent elemental images. It means that the over-sampled elemental image array can be generated without lens movement in the pickup procedure. Finally, the display stage of DM is exactly the same as the OM display.

B. Direction Information

Going back to the principles of II, each elemental image in the array should contain not only intensity but also direction information. The use of replication or linear interpolation considers only intensity so we need to add direction information.

In order to understand the direction information contained in an elemental image, we analyze a simple pickup II system by ray sampling. In Fig. 6, we simplified the pickup procedure of conventional II with two micro-lenses and their corresponding elemental images. We consider three objects at a distance d from the lenslet array, and two elemental images of them: the upper and lower elemental image.

Due to the restricted size of the corresponding elemental cell, in the upper elemental image only objects 1 and 2 are recorded. However, in the lower elemental image only objects 2 and 3 are recorded. From this observation, we can declare two regions at each elemental image: a white region and a gray region. For both elemental images the white region corresponds to object 2 and corresponds to the similar information. The gray region in the upper elemental image records object 1 while the gray region

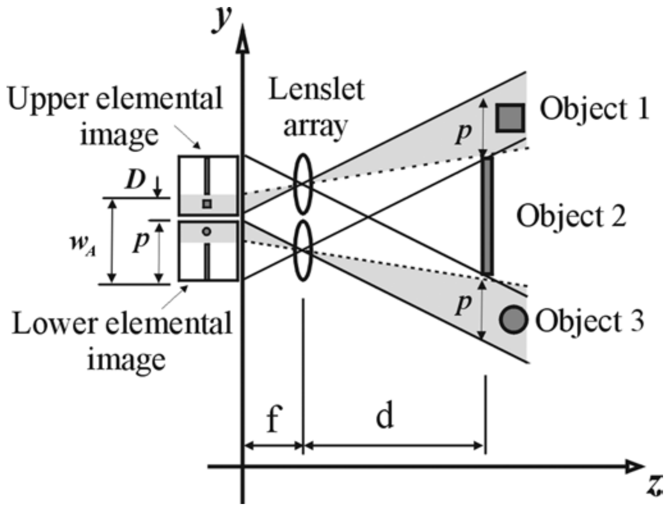

Fig. 6. Three objects are recorded in two elemental images and analyzed by ray sampling. Object 2 in white area is similar information for upper and lower elemental-image. Objects 1 and 3 are different information for each other elemental-image.

in the lower elemental image records object 3. Because of this, these regions correspond to the information that is different by the other elemental image. Both regions are limited by a width size D, which can be easily calculated using geometrical optics, obtaining an expression as

$$D = \frac{pf}{d - f} \tag{8}$$

This longitudinal distance D helps to identify the more related pixels between neighbor images.

C. Implementation of DM Method

The direction information can be roughly related with the distance D that identifies the more related pixels between one elemental image and its nearest neighbor. Then we propose a simple algorithm that calculates a new middle elemental image as follows: the neighbors elemental images are divided by the definition of D, the similar information of both images are averaging and the different information are replicated, finally the size of the new image is set cutting both edges by a strap of $D/2$ pixels wide.

The new middle elemental image should have object 2 in the middle of the image and at the edges should appears half part of objects 1 and 3, which means that a middle image should have a new distance D' equal to $D/2$. Fig. 7 shows a scheme of this procedure.

The new middle elemental image is interlaced between original elemental images. This procedure is done along the elemental image rows in the array in order to enlarge in the x direction. As a second step the x direction enlarged array is processed along the columns in order to obtain the y direction magnification to complete the digital magnification. We define N_x and N_y as the number of elemental images in the original elemental image array in each direction, then the over-sampled elemental image array contains $(2N_x - 1) \times (2N_y - 1)$ elemental images.

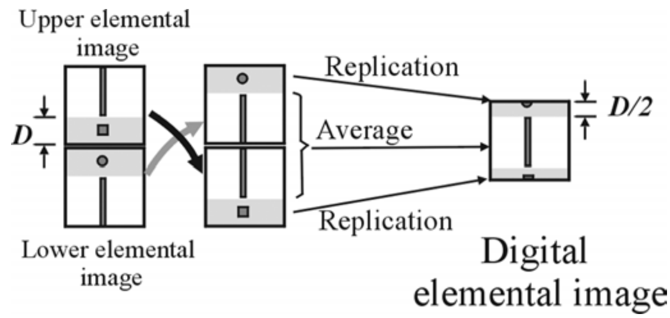

Fig. 7. For the implementation method of the DM method, from the upper and lower elemental images we identify the similar information and average this part, also different information in order to replicate. The final digital elemental image is cut at both edges as $D/2$.

Fig. 8. Experimental objects: button with a footprint on it and button with a peace mark on it.

For an integer magnification factor, we need to pay a special attention to the edges adding a zero image to the original array in order to extrapolate a new elemental image.

IV. Experimental Setup and Results

We magnified two small objects by a factor of two with the OM and DM methods respectively. Our goal is to reconstruct clear 3-D integral images when we use the DM method.

A. Experimental Setup

In the pickup procedure, we used a microlenslet array which has pitch p equal to 1.09 mm and the separation between lenses is less than 7.6×10^{-3} mm. The focal length of each lens is 3 mm. Only 23×16 lenslets were used to record the experimental objects. Each elemental image had 58×58 pixels that were captured using a CCD with a total numbers of 3152×2068 pixels, not all pixels are used for recording purposes.

We used two objects in our experiment: a button with a footprint on it and a button with a peace mark on it, as shown in Fig. 8. The diameter of both objects is 10 mm; the gap distance between the lenslet array and the first object is 26 mm and the distance between them is approximately 8 mm. The peace mark has lines of 1.0 mm wide, and the footprint small details are of ~1.0 mm as well. Those features allow us to identify whether the reconstructed 3-D II has enough quality or not.

In the display procedure, we used projection type II which uses a micro-convex mirror array to reconstruct the 3-D integral image. An LCD projector (RGB) displays the elemental image array in three different panels, each one display one channel of the color image. Each panel has the following characteristics:

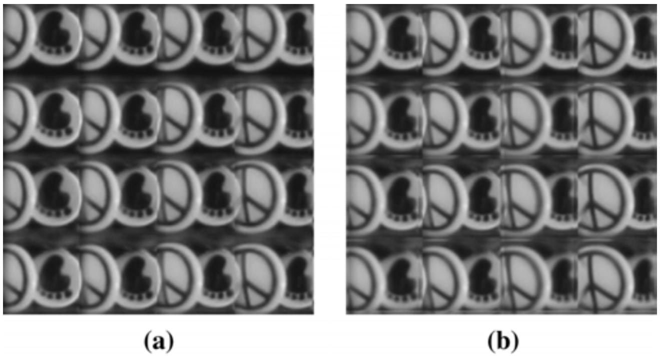

Fig. 9. Elemental image arrays that are magnified by factor two. (a) The Optical Magnification method. (b) Digital Magnification Method.

1024×768 pixels and the pixel pitch is 18 μm, not all pixels are used to display the elemental image array. The diverging angle of the projection beam is approximately $\theta = 1.4°$. The same microlenslet array used in the pickup procedure is used in the reconstruction setup, but now working as a micro-convex mirror array. The microlenslet array does not have coating then it has small reflectivity due the transparent optic material. In this case, the focal length of each convex mirror in the array is 0.75 mm. When displaying the original elemental images we used 23×16 micro-convex mirrors. On the contrary, in the display procedure of the OM and DM elemental-image arrays we used 46×32 mirrors.

B. Experimental Elemental-Image Arrays

Considering optical magnification by a factor of two, we picked up four elemental images by MALT at four sampling positions, $c_{0,0}^{k,l}$, $c_{0,0.545}^{k,l}$, $c_{0.545,0}^{k,l}$, $c_{0.545,0.545}^{k,l}$ (all in millimeters). These positions correspond to an interval half of the pitch of the lenslet array. Fig. 9(a) shows 4×4 elements out of the optical magnified array which have precise optical information about the objects.

We consider the $c_{0,0}^{k,l}$ elemental image array as an input of the DM method to be magnified. Fig. 9(b) shows 4×4 elemental images out of the array magnified digitally. In this case, D from (8) is about 6 pixels for both objects.

C. Mean Square Error of Elemental-Image Arrays

We evaluated mean square error (MSE) [24] of the elemental images obtained by the digital magnification method comparing them with the elemental images obtained by optical magnification method. This calculation gives a numerical comparison. The images have three channels (RGB) with 256 gray levels. We obtained a MSE value as 172, which is small value compared with 803 MSE value when we use only replication of elemental images for digital magnification.

The value of MSE can be explained for two main reasons: alignment problem when an optical magnified elemental image array is arranged, and the mathematical error in the digital calculation of the new elemental images. Ideal MSE value should approach zero.

D. Numerical Evaluation of Longitudinal Magnification

In order to prove the real magnification of a 3-D object, we made a numerical evaluation of longitudinal or depth magnification. We use a 3-D II technique that computationally reconstructs the 3-D scene as a 3-D volumetric image [26]–[28]. Image display planes are computed for arbitrary distances from the lenslet array by back propagating the elemental images through a virtual pinhole array. The computation and reconstruction is based on ray optics.

Three volumetric reconstructions were obtained for original, optical magnified and digital magnified elemental image arrays. Fig. 10 shows the reconstructed image planes for the button with a footprint on it and button with a peace mark on it. This results show that the magnification changes the location of the plane of the reconstruction m times far from the lenslet compared with original reconstruction, where m is the magnification factor.

The calculated depth for the original objects was 8.5 mm as show in Fig. 10(a). In Fig. 10(b) the reconstructed planes for optical magnified objects has a depth of 17 mm, this means that the longitudinal magnification is equal to the lateral magnification. Digital magnification has a depth equal to 17 mm similar to optical magnification, as is shown in Fig. 10(c).

This numerical evaluation proves the true 3-D magnification for both optical and digital methods. It means that lateral magnification and longitudinal magnification has the same factor. Also we appreciate the similarity between optical and digital magnification techniques.

E. 3-D Optical Reconstructed Integral Image

Experimental reconstruction results are shown in Fig. 11. Fig. 11(a) is a 3-D reconstructed integral image without magnification. Fig. 11(b) is the 3-D reconstructed integral image magnified by the OM method. Fig. 11(c) is a digital magnified 3-D reconstructed integral image.

Magnification is proved by visual comparison between original reconstruction and both magnified reconstructions. Visual appearance of magnified reconstruction are clear, it means the elemental images have almost accurate direction information. This similarity proves the same behavior of DM compared with optical magnification.

V. Conclusions and Remarks

In this paper, we proposed a simple digital magnification method applied to 3-D integral imaging using interpolation principles. When we use a digital magnification method in integral imaging, adjacent elemental images are used for calculation of new middle elemental images. The new elemental images are generated by average and replication of information of the neighbor elemental images.

In this simple algorithm the direction information is related with the calculation of D which defines the information in the elemental image to be average or replicate. Consequently, when we used a digital magnification method with direction information, we can magnify small objects without lens movement and quality degradation of the reconstructed 3-D integral images.

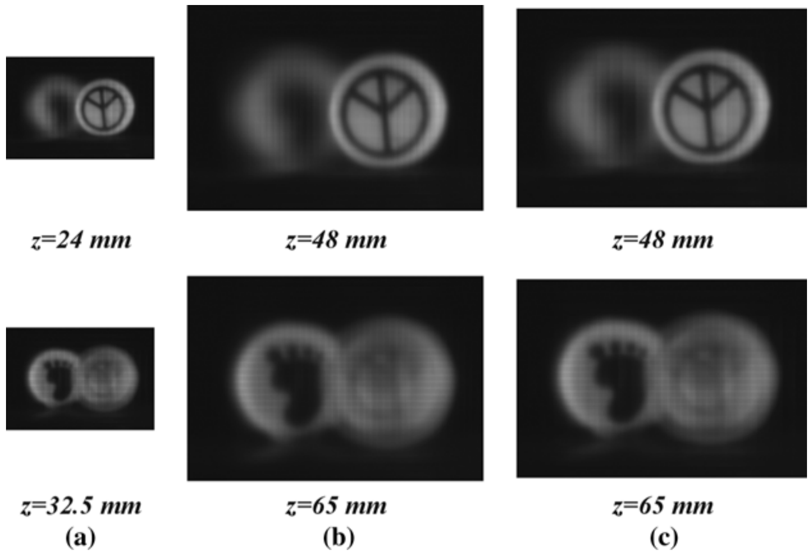

Fig. 10. Digital 3-D Volumetric Optical reconstruction shows the reconstruction planes for button with a footprint on it and button with a peace mark on it, in order to calculate the depth of the scene. (a) No magnification $\Delta z = 8.5$ mm (b) The optical magnification method moves the object plane two times farther from the virtual pin-hole than original reconstruction $\Delta z = 17$ mm. (c) the digital magnification method has the same characteristics than optical magnification method $\Delta z = 17$ mm.

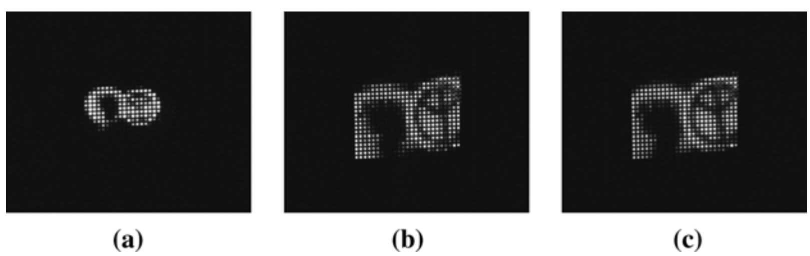

Fig. 11. Optical reconstruction of 3-D II images. (a) No magnification. (b) Optical magnification method. (c) Digital magnification method.

However, using a digital magnification method alone to magnify the object increases error rate of elemental images in proportion to the magnification factor. Therefore we can propose the use of optical magnification in a first step following by a digital magnification method in order to obtain higher magnification factors and attain a good quality image with less complexity.

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