Multiple-Planes Pseudoscopic-to-Orthoscopic Conversion for 3D Integral Imaging Display

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***Abstract*—In this paper, we propose an advanced pseudoscopic-to-orthoscopic conversion method for 3D integral imaging display systems. Compared to previous works, this method can generate more accurate images for orthoscopic 3D display using multiple reference planes and estimated depth information. 3D display results show the superiority of the proposed pseudoscopic-to-orthoscopic conversion method.**

***Index Terms*—Integral imaging, pseudoscopic-to-orthoscopic conversion, 3D display.**

I. Introduction

UNLIKE traditional stereoscopic 3D display techniques [1], [2], integral imaging [3]–[22] as one of autostereoscopic systems, can allow viewers to observe reconstructed images without the need for special glasses. Integral imaging, first proposed by G. Lippmann in 1908 [3], uses a lenslet array to record and reconstruct the light rays coming from a naturally-illuminated 3D object. Integral imaging is one of the upcoming promising 3D display techniques.

In integral imaging 3D display system, the displayed images are pseudoscopic if the captured 2-D images are not pre-processed. The pseudoscopic nature means that the displayed depth of objects is reversed when compared to the original 3D scene. Fig. 1 shows the pickup process and display process of integral imaging. As shown in Fig. 1(b), the 3D images which the viewer observes are pseudoscopic real images (the objects located at far distances from the pickup plane are displayed close to the observer). In order to represent the original 3D scene with correct depth in the display process, conversion from pseudoscopic images to orthoscopic images is necessary. Orthoscopic images can be displayed with correct depth.

Some works has been proposed to solve the depth-reversed problem in integral imaging 3D display. An efficient digital method to display orthoscopic 3D scenes was first proposed in [23]. By rotating the captured 2-D images by 180 degrees, we can obtain orthoscopic virtual images (3D scenes appear inside the display panel). Although the method is easy to implement, it can only provide virtual reconstructions. Other approaches [24]–[27] have been studied to genereate real and virtual 3D reconstructions by virtually generating an image array from the captured image array. A generalized algorithm proposed in [27] can perform the pseudoscopic-to-orthoscopic (PO) transformation with various display parameters and control the depth and size of the reconstructed 3D scene. This smart PO conversion (SPOC) approach uses the elemental images captured in the integral imaging pickup to simulate a virtual pickup process by setting a pinhole plane and an imaging plane. To map the pixels from the real pickup plane to the virtual pinhole plane, a reference plane (RP) is utilized and assumed to be the position of 3D scene. This approach can generate satisfactory results when objects are located close to the position of the reference plane. However, when objects are far away from the reference plane, pixel-mapping errors occur and the 3D display qualities are degraded. To reduce the errors of pixel mapping and achieve improved 3D display results, we propose a PO conversion method by setting up multiple reference planes based on estimated depth information. The paper is organized as follows. In Section II, we analyze the problems of the smart PO conversion method. Section III describes the proposed conversion method. 3D display results using SPOC and the proposed method are compared in Section IV followed by conclusions in Section V.

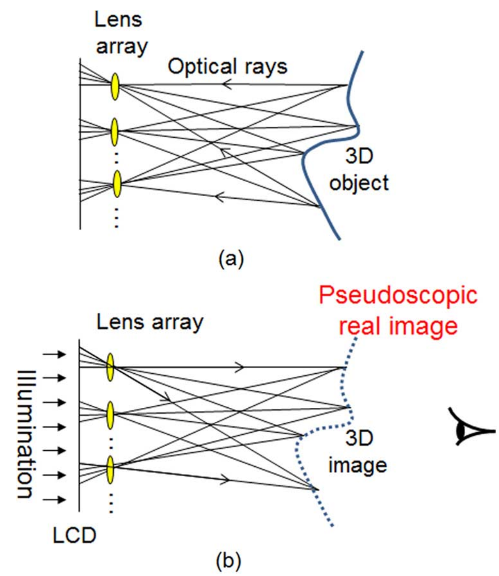

Fig. 1. (a) Pickup process and (b) display process of an integral imaging system.

Manuscript received July 20, 2014; revised December 20, 2014; accepted December 22, 2014. Date of publication January 06, 2015; date of current version October 16, 2015. This work was supported in part by Samsung Electronics Inc. under the Samsung Advanced Institute of Technology (SAIT) Global Research Outreach (GRO) Program.

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Digital Object Identifier 10.1109/JDT.2014.2387854

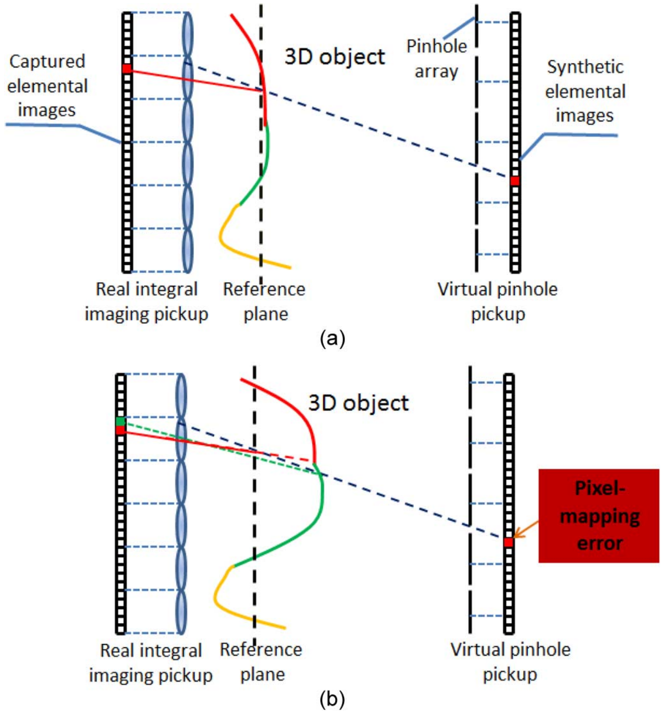

Fig. 2. (a) Diagram of smart pseudoscopic-to-orthoscopic conversion method. (b) Pixel-mapping errors in SPOC.

II. Problems on Smart Pseudoscopic-to-Orthoscopic Conversion Method

Smart PO conversion method (SPOC) [27] generates synthetic elemental images from the captured elemental images for orthoscopic 3D integral imaging display. As shown in Fig. 2(a), this approach sets up a reference plane close to the 3D object. In addition, a virtual pinhole array and an imaging plane are set up based on the constraints of display device. To obtain synthetic elemental images in the virtual pinhole pickup process, a virtual ray (blue dash line) is first projected back from the virtual pinhole. After that, another ray (red line) is back-projected from the intersection of the reference plane (black dash line) and the virtual ray through the lens used in real integral imaging pickup. This method assumes that 3D objects are near to the reference plane. However, for a 3D scene with large range of depth, it is difficult to select one reference plane close to all the regions of the scene. In this case, pixel-mapping errors may occur for the regions far away from the reference plane [see Fig. 2(b)]. As shown in Fig. 2(b), the corresponding pixel on synthetic elemental images should be the green one from the captured elemental images instead of the red one. In addition, the sizes of 3D objects on synthetic elemental images may be either reduced or enlarged compared to the ones captured with a real imaging system because the position of the reference plane is different with the real positions of 3D objects.

III. Multiple-Planes Pseudoscopic-to-Orthoscopic Conversion Method

To generate more accurate synthetic elemental images for orthoscopic 3D integral imaging display, we propose an advanced pseudoscopic-to-orthoscopic conversion method by setting up multiple reference planes based on estimated depth information.

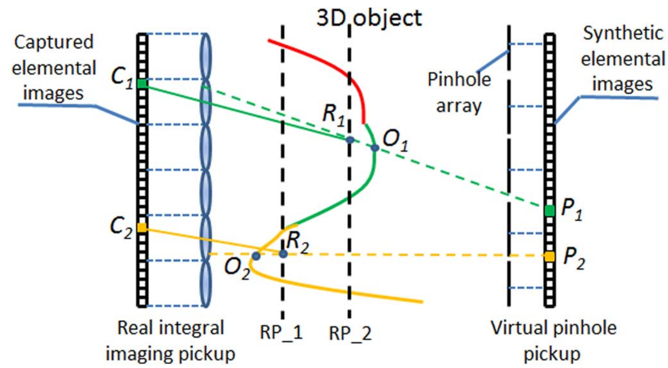

Fig. 3. Diagram of multiple planes pseudoscopic-to-orthoscopic conversion method.

The main idea is to utilize multiple reference planes to split the 3D scene into several regions and to implement pixel-mapping by selecting one of the reference planes. The selected reference plane is the one which is the nearest to the objects. Note that depth information is needed in this approach. The number and the positions of reference planes depend on the depth of a 3D scene.

The algorithm can be summarized in the following steps.

Step 1) Estimating depth information [28]–[30] of the 3D scene.

Step 2) Calculating the number and the positions of the reference planes based on the depth of the 3D scene.

Step 3) Implement pixel-mapping using the selected reference plane, which has minimum distance from the objects. The pixel mapping method is the same as the one used in SPOC.

To further explain the approach, we assume that two reference planes (RP_1 and RP_2) are set up to cover the depth of the 3D objects (see Fig. 3). To locate the corresponding pixel for P_1 from the captured elemental images, we first back-project it and the virtual ray (green dash line) intersects the object at O_1. Because O_1 is closer to RP_2, we find the mapping pixel (C_1) by projecting back from the intersection (R_1) of the reference plane (RP_2) and the virtual ray. Similarly, for P_2, RP_1 is selected because O_2 is closer to it and C_2 is the mapping pixel projecting from R_2 to the captured elemental images. By setting up multiple reference planes, the pixel-mapping error (described in Section II) can be reduced especially for the case that objects are located far away from the reference plane.

To decide the number and the positions of reference planes, we can implement two different methods for a simple scene case and a complex scene case. A simple scene means that there are a few relatively small-sized objects separately located in 3D space. In this case, we can utilize cluster algorithms for the estimated depth information. The number of clusters is the number of reference planes and the cluster centers are set as the positions of the reference planes. By comparisons, a complex scene means that the objects have relatively large sizes and thickness and they are continuously distributed in the whole 3D space. In this case, we can directly split the 3D scene into several subregions and the centers of these subregions are set as the positions of the reference planes.

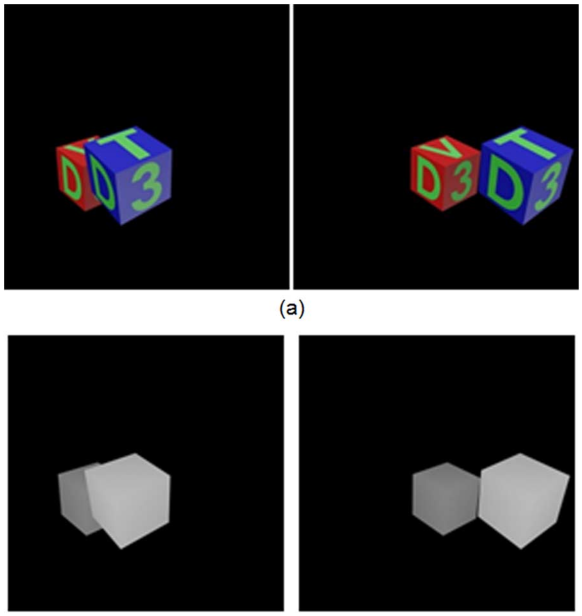

Fig. 4. Simple 3D scene generated by 3D Max. (a) Two examples of elemental images. (b) Depth information (the darker color represents farther distance).

TABLE I
SPECIFICATIONS OF INTEGRAL IMAGING PICKUP PROCESS

Description	Parameters
Total number of elemental images (EIs)	11(H) × 13(V)
Pixel number on each EI	2000(H) × 2000(V)
Sensor pitch	10mm(H) × 10mm(V)
Field of view of each sensor	45 degree
Angular resolution	0.0225 degree
Distances between the centers of objects and the pickup plane	Blue dice: 130mm Red dice: 210mm
Object sizes	Blue box: 40mm Red box: 30mm

Note that the computation time of the proposed method is linearly proportional to the number of reference planes. Considering that the display device has a certain depth of field and intensities of the objects are locally smooth and continuous, it is not necessary to set up as many reference planes as possible.

IV. 3D INTEGRAL IMAGING DISPLAY RESULTS

To show the advantages of the multiple-planes pseudoscopic-to-orthoscopic conversion method (MP-POC), we conducted two groups of display experiments. One group of images is obtained by simulating the real integral imaging pickup process in 3D Max. The other group is captured using synthetic aperture integral imaging technique [17].

Fig. 4 shows two examples of the elemental images and the depth information generated from 3D Max. Two die with some characters are separately located in 3D space. The parameters for simulating integral imaging pickup process are listed in Table I. We consider the scene as a simple 3D scene.

TABLE II
SPECIFICATIONS OF INTEGRAL IMAGING 3D DISPLAY

Description	Parameters
Display device	HTC ONE smart phone
Size of display panel	Approx. 10.2cm(H) × 5.7cm(V)
Resolution of display device	1920(H) × 1080(V)
Pixel size of display device	54.2 μm
Total number of elemental images (EIs)	96(H) × 54(V)
Pixel number on each EI	20(H) × 20(V)
Pitch of microlens array	1mm
Focal length of microlens	3.3mm

To calculate the number and the positions of reference planes, we utilized the k-means cluster algorithm to implement depth clustering. We obtained two clusters and the centers of each cluster are 132 mm and 207 mm. Therefore, the number of reference planes is two and the positions are set at 132 mm and 207 mm, respectively. In the display process, we used an HTC ONE smart phone as our display device and the parameters for 3D integral imaging display are given in Table II. The distance between the microlens array and the display panel equals the focal length of microlens. In order to achieve high-quality display results for the whole 3D scene, we put the display plane at the center of 3D scene. Therefore, the display plane is located at 170 mm away from the pickup plane. In integral imaging display, 3D images of blue dice are real, located at approximately 20 mm $\sim$ 60 mm in front of the display panel and the 3D images of red dice are virtual located at approximately 20 mm–60 mm behind display panel.

The generated elemental image sets for 3D displays by using the proposed MP-POC and the previous method (SPOC) are shown in Fig. 5. The image details enlarged in Fig. 5 show that MP-POC can generate more accurate images of 3D objects. The display results on the HTC ONE smart phone by using these four groups of generated elemental images (Fig. 5) are shown in Fig. 6 for right view, front view and left view, respectively. We can see that the displayed objects using the proposed MP-POC are smoother and less distorted than the ones obtained by using the SPOC.

To carry out our second display experiment, we obtained the elemental images of real 3D scene by using the synthetic-aperture integral imaging technique, as shown in Fig. 7(a). In this experiment three objects were distributed in the range of 280 mm $\sim$ 400 mm from the camera array. The depth is estimated by minimizing the variance of the positions of back-projected rays in integral imaging system [28] [see Fig. 7(b)]. For such a complex scene, we segmented the space into several subregions. Based on depth of field of 3D display systems, we found that each subregion should be of around 30 mm $\sim$ 40 mm. Here, we divided the 3D scene into 3 subregions of 40 mm. The positions of reference planes were then set at 300 mm, 340 mm, and 380 mm from the camera array plane.

The generated elemental images for 3D displays by using the proposed MP-POC and the conventional SPOC are shown in

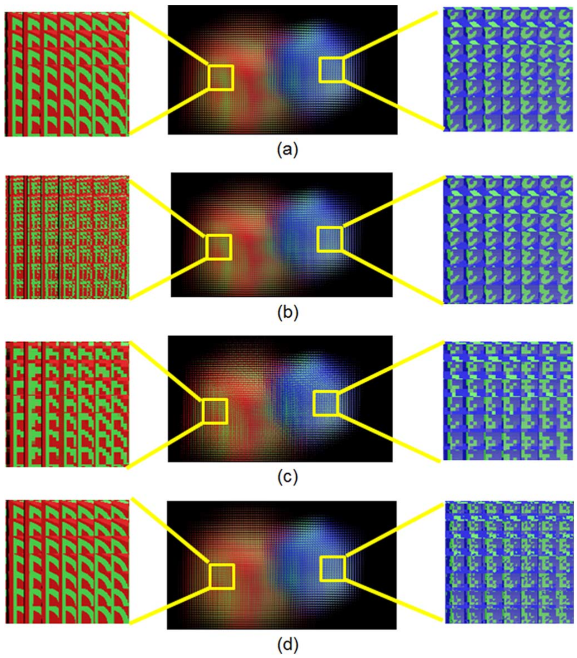

Fig. 5. Generated elemental image sets for 3D display by using (a) the proposed MP-POC method with two reference planes located at 132 and 207 mm and (b)–(d) the SPOC method with one reference plane located at 132 mm (the center position of blue box), 170 mm (the center of the scene), and 207 mm (the center position of the red box), respectively. Pixel mapping error in the generated elemental images can be reduced by using the proposed MP-POC method.

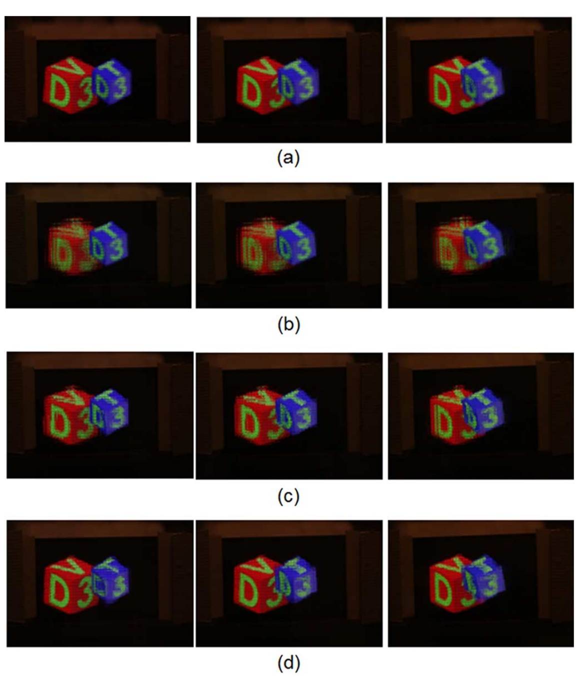

Fig. 6. Display results captured from right view, front view, and left view by using (a) the proposed MP-POC method with two reference planes (132 and 207 mm) and (b)–(d) the SPOC method with single reference plane at 132, 170, and 207 mm, respectively.

Fig. 8. The MP-POC method used three reference planes located at 300 mm, 340 mm and 380 mm; the conventional SPOC method used one reference plane located at 340 mm. The display plane is also placed at 340 mm away from the pickup plane.

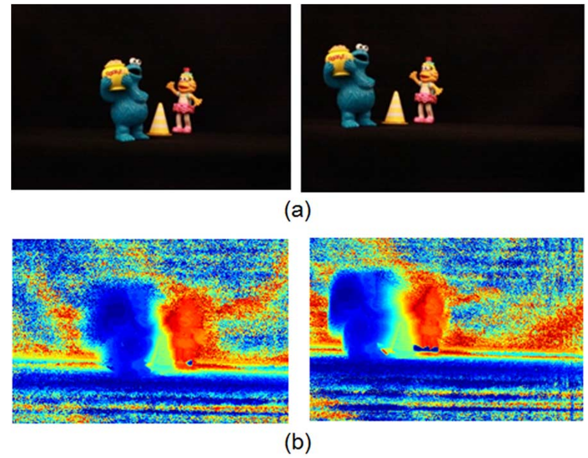

Fig. 7. 3D scene captured by using synthetic aperture integral imaging technique. (a) Subsets of elemental images. (b) Depth information (cooler color represents nearer objects).

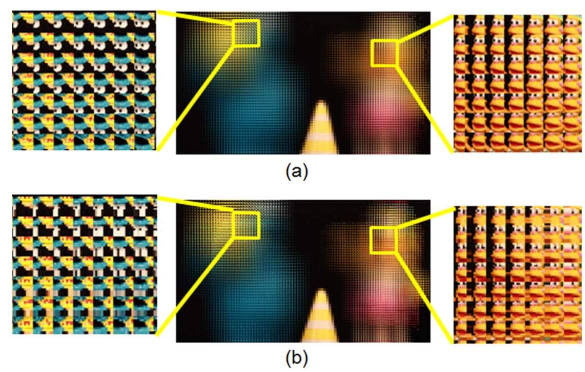

Fig. 8. Generated elemental image sets for 3D displays by using (a) the proposed MP-POC method with three reference planes located at 300, 340, and 380 mm. (b) The SPOC method with one reference plane at 340 mm (the center of the 3D scene). Pixel mapping error in the generated elemental images can be reduced by using the proposed MP-POC method.

In the 3D display, the blue cartoon was reconstructed at the region of 30 mm $\sim$ 60 mm in front of display panel and the pink cartoon at 30 mm $\sim$ 60 mm behind display panel. Fig. 9 shows the display results from right view, front view, and left view for MP-POC and SPOC methods. Display results show that the details of the objects (the eyes, and the mouths of cartoons etc.) can be displayed more clearly by using the proposed MP-POC method.

Based on the experimental results, the high-quality 3D displayed region can be enlarged from 30 mm to 120 mm. Note that the proposed method needs extra computational time due to the depth estimation. Recently, computational integral imaging with GPUs has demonstrated substantial improvements in computational tasks [31] which may benefit the depth estimation described in this paper.

V. Conclusion

To solve the depth-reversed problem in integral imaging 3D display systems, we have presented an advanced pseudoscopic

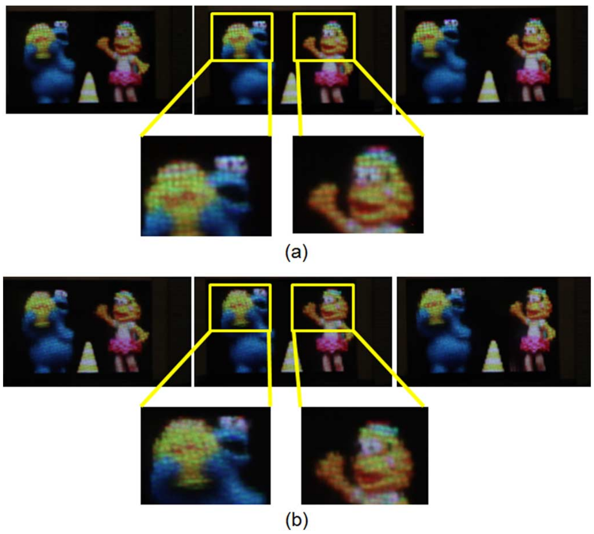

Fig. 9. Display results from the right view, front view and left view by using (a) the proposed MP-POC method with three reference planes located at 300, 340, and 380 mm and (b) the SPOC method with one reference plane located at 340 mm (the center of the 3D scene). Details of objects (e.g., the eyes and the mouths of the cartoons) can be displayed more clearly by using the proposed MP-POC method.

to orthoscopic conversion method by setting up multiple reference planes based on depth estimation information. The proposed conversion method can reduce the pixel-mapping errors for deep scenes during the generation process of synthetic elemental images. 3D display results for different scenarios have been demonstrated and verified the advantages of the proposed multiple-planes pseudoscopic-to-orthoscopic method.

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