Solution of pseudoscopic problem in integral imaging for real-time processing

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Proposed is a very effective conversion method from pseudoscopic (PS) to orthoscopic elemental image with adjustable depth position of a reconstructed three-dimensional (3D) object for integral imaging (InIm) in real-time. The proposed method is based on the interweaving process in multi-view display (MVD) with consideration of the difference between the ray sampling method of MVD and InIm. The simple transformation matrix formalism enables the real-time conversion from pickup image to display image based on InIm without a PS problem.

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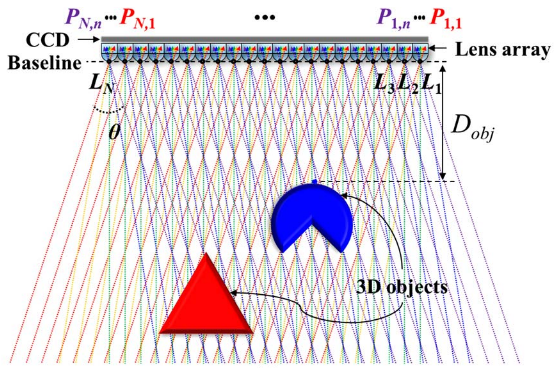
Integral imaging (InIm) proposed by Lippmann in 1908 is one of the most intensely researched methods in autostereoscopic three-dimensional (3D) display [1]. Although InIm has many advantages, its characteristics are fundamentally limited by specification of lens array and display panel. Above all, the major issue for 3D broadcasting based on InIm is a pseudoscopic (PS) problem, known as the inevitable bottleneck for real-time pickup and display systems. The PS problem in InIm arises from different directions of pickup and display as shown in Fig. 1.

In pickup phase, the light scattered from the 3D object, which is passing through each lens L_i within viewing angle θ, forms the elemental image (EI). The rays are captured by a charge-coupled device (CCD) as shown in Fig. 1(a). On the other hand, in display phase, the 3D object is reconstructed by the EI and the same lens array used in pickup phase. The observer watches the rear side of the reconstructed 3D image in the direction from the 3D object to lens array as shown in Fig. 1(b). Therefore, the typical EI, without any kind of additional process or transformation method, cannot avoid the PS problem. To overcome this fundamental drawback, various methods, which are conversion methods from PS to orthoscopic (OR) EI, have been proposed by many research groups [2–7].

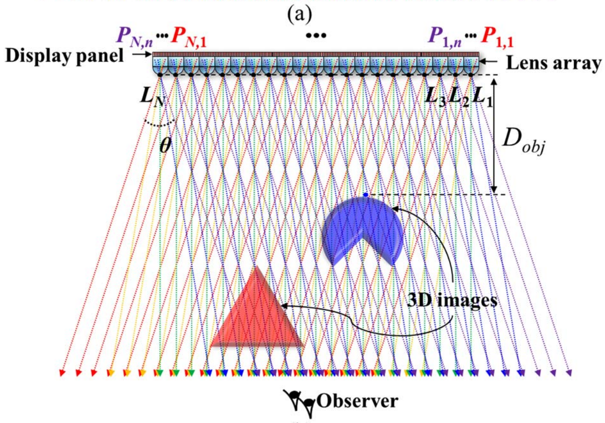
In the initial stage of research about the PS problem, Ives proposed a two-step InIm method, which recaptures an integrated 3D image by an additional pickup setup [2], and Arai *et al.* used the graded index lens array for capturing real a 3D object without the PS problem [3]. However, these methods need expensive optical elements or an additional pickup phase, which induces degradation and loss of the light information. With the development of computational technology, some other PS to OR conversion methods based on computational pickup and transformation have been proposed [4–7].

Okano *et al.* proposed the simplest method which can achieve the virtual-OR EI from the real-PS EI by rotating an EI by 180 deg [4], and Martínez-Corral *et al.* proposed a noticeable method, smart pixel mapping (SPM), which is based on the virtual pickup of a reconstructed 3D image with virtual pinhole array [5]. SPM and its modified methods are feasible to acquire and display a real 3D object without the PS problem [5–7]. However, the depth position of a reconstructed 3D object is fixed or limited and these methods are hard to process in real-time because of the computational load for interpolation.

In this Letter, we propose the simple solution of the PS problem in InIm for real-time process, which is based on the difference between multi-view display (MVD) and InIm. The purpose of the proposed method is the realization of a real-time 3D broadcasting environment of InIm, and for it to be as simple as possible. We invented the simple mapping method for real-time processing and cost



(a)



(b)

Fig. 1. (Color online) Principle of InIm with PS problem: (a) concept of pickup phase with N lenses with n pixels of camera corresponding to each lens and (b) display phase in InIm with PS problem.

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effectiveness by using a modification of the interweaving process (IWP) in MVD. In addition, the adjustable depth position of a reconstructed 3D object is also realized in the proposed method by using quasi-continuous viewpoints and periodic depth planes of InIm.

The fundamental principle of autostereoscopic 3D displays is very similar except for the usage of different optical devices. However, MVD is generally not concerned about the PS problem because it has the definitive solution, the IWP [8]. To solve the PS problem in MVD, the baseline of pickup cameras and camera positions are corresponding to the viewing distance D and viewpoints to keep the relative position and direction as shown in Fig. 2. From the geometrical equivalence of pickup and display phase, N pixels of acquired n-view images are simply mapped to each n-pixel on the display panel behind N lenses when the pixel and lens pitches of pickup phase and display phase are equal each to the other.

Consequently, acquired n-view images can be alternately interwoven to one image on the display panel because of the sampling with converged rays. From the IWP in MVD, we adopt the IWP to InIm to solve the PO problem. However, InIm and MVD have fundamentally different ray sampling methods as shown in Figs. 1 and 2. In MVD, the principal rays in each camera are converged at the convergence point on the object plane apart by the viewing distance D, and the field of view of each camera is sufficiently large enough to capture the identical object plane. Therefore, the IWP is simplified by the identical pickup and display setup.

On the other hand, the IWP of MVD cannot be adopted to InIm because the rays passing through the lens array from pixels on the display panel in InIm are not converging at a certain point and cannot form the viewing distance and viewpoints. This is the reason why InIm can give quasi-continuous viewpoints. Unlike the MVD, the viewpoints of InIm are formed at several depth planes within the viewing angle as shown in Fig. 1(b).

Before performing the modified IWP for InIm, the viewpoints in the display and baseline of pickup cameras have to be matched in each depth plane like in MVD. All viewpoints in InIm are widely distributed within the viewing angle, and only focused viewpoints are periodically formed on several depth planes with regular distance [9]. The regular interval of depth planes is determined by the specification of lens array and display panel as follows:

$$D_k = kfp_l(n-1), \tag{1}$$

where focal length is f, lens pitch is p_l, and the number of pixels in one EI is n. The maximum number of reconstructed depth planes $k_{\max}$ is derived as follows:

$$k_{\max} = \lfloor N/(n-1) \rfloor, \tag{2}$$

where $\lfloor x \rfloor$ is floor function of x, and the number of lens array is N. Therefore, the baseline of pickup phase is selected to the viewpoints of display phase on the one

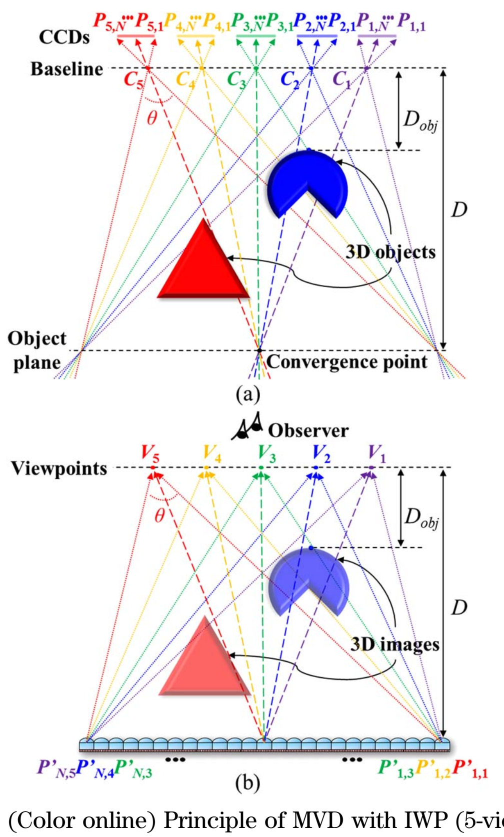

Fig. 2. (Color online) Principle of MVD with IWP (5-view display): (a) principle of MVD in pickup phase with multi-camera C and its acquired pixels P and (b) display phase with mapped pixel P' in IWP.

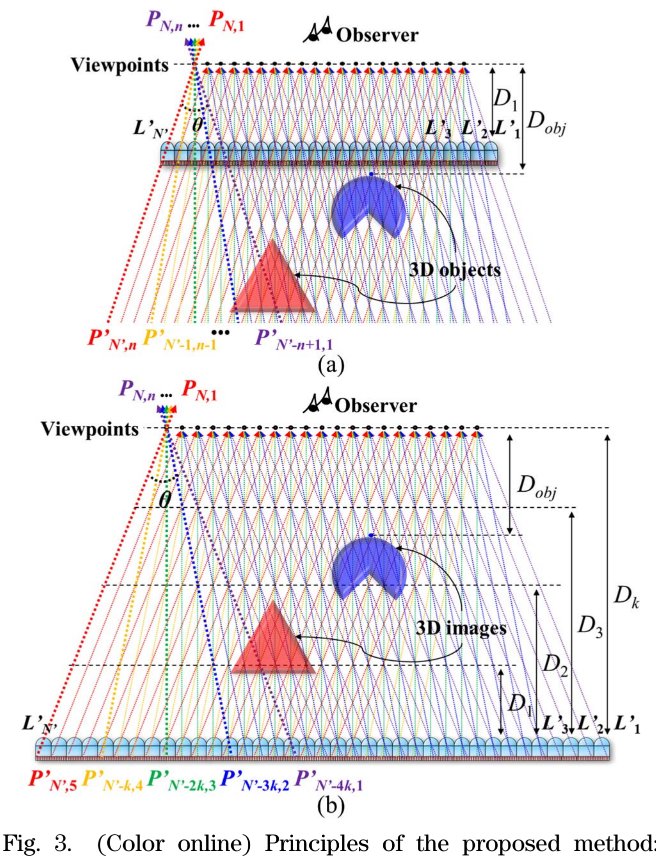

Fig. 3. (Color online) Principles of the proposed method: (a) concept of the proposed method with nearest depth plane (D_1) and (b) with arbitrary depth plane (D_k) corresponding to viewpoints.

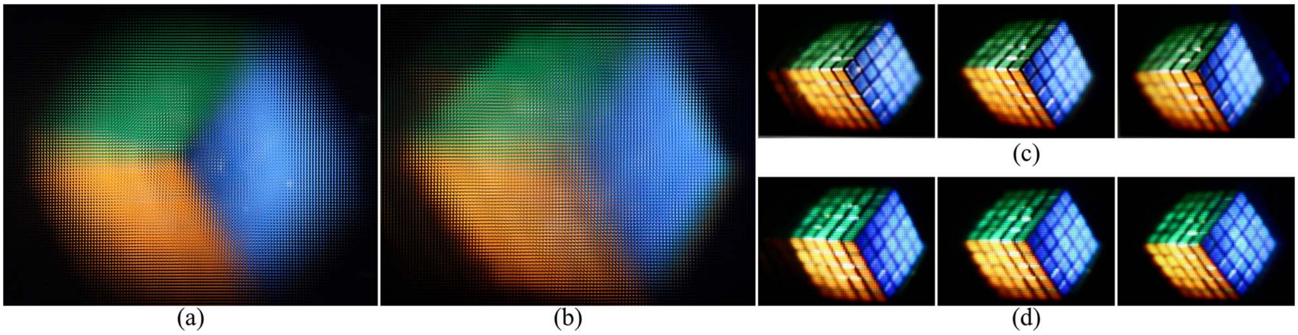

Fig. 4. (Color online) Experimental results: (a) EI with PS problem, (b) converted EI using proposed method ($k = 3$), (c) leftmost, center, and rightmost views of reconstructed 3D image from EI with PS problem (Media 1), and (d) from converted EI (Media 2).

of k_{max} depth planes, and the number of viewpoints is the same as the number of lenses in pickup phase N. If the k-th depth plane is selected as the viewpoints, the number of lenses for display process N'_k has to increase as follows:

$$N'_k = N + k(n - 1). \tag{3}$$

Figure 3 shows the mapping process of the proposed method. From the correspondence between viewpoints on arbitrary k-th depth plane and EI, the s-th and t-th pixel in i-th and j-th EI $p_{(i,j),(s,t)}$ is mapped to the s'-th and t'-th pixel in i'-th and j'-th EI $p'_{(i',j'),(s',t')}$ with following transformation matrix.

$$\begin{pmatrix} i' \\ j' \\ s' \\ t' \end{pmatrix} = \begin{pmatrix} 1 & 0 & -k & 0 \\ 0 & 1 & 0 & -k \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} i \\ j \\ s \\ t \end{pmatrix} + \begin{pmatrix} kn \\ kn \\ n+1 \\ n+1 \end{pmatrix}. \tag{4}$$

As shown in Fig. 3(a), if the depth plane for display phase is selected on the nearest depth plane from lens array D_1, the result of the mapping process is almost the same as SPM. However, if the depth position of 3D object D_{obj} is smaller than D_1, the EI is converted from PS-real to OR-virtual image. It is the weak point of SPM because D_1 is generally too narrow to acquire the whole volume of information of the 3D object [5]. In addition, the smart PS-to-OR conversion (SPOC) method needs high resolution capturing and an additional interpolation method for setting an arbitrary depth plane, although it is the most generalized method [7]. From these drawbacks, SPM and SPOC are not suitable to be applied to the real-time pickup and display system based on InIm.

On the other hand, the proposed method can realize the real-time PS-OR conversion using a simple transformation matrix in InIm, which can also adjust the depth position of reconstructed a 3D object within the range of depth planes k_{max} as shown in Fig. 3(b). Therefore, the proposed method can be the complementary method of previous researches.

We perform the experiment to verify the proposed method. For the acquirements of a real 3D object to EI, we use Canon 5D Mark II camera and lens array with 1 mm pitch and 3.3 mm focal length. The real 3D object is Rubik's cube located 80 mm in front of lens array with 70 mm depth. The display setup for reconstructing a 3D object is composed of Apple new iPad with 0.096 mm pixel pitch and lens array used in pickup phase. Therefore, the number of pixels in one EI n is approximately 10 and the depth interval D_1 is 29.7 mm from Eq. (1). In this experimental setup, the depth plane number k has to be larger than 3 for a real-OR image because the depth position of the object is larger than D_1.

Figure 4(a) shows the acquired EI of Rubik's cube, and Fig. 4(b) shows the converted EI using the proposed method. The elapsed time for the conversion of EI with 1320 by 1060 resolution is 10.3 ms in an Intel Core i5 processor, which is enough to convert from PO to OR in real-time. Figures 4(c) and 4(d) show the reconstructed view images in different view positions from leftmost to rightmost. By the relative movement of camera and border of EI box, the PS image (Media 1) shows the reversed depth information and the converted OR image (Media 2) shows the correct information of a 3D object.

In conclusion, the proposed method can simply solve the PS problem of InIm in real-time and arbitrary adjust the depth position of a reconstructed 3D object for 3D broadcasting.

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