# Progress in 3-D Multiperspective Display by Integral Imaging

Viewing of realistic projected 3-D images without using any additional devices is achieved by high-resolution displays, rapid digital image processing, and improved fabrication of microlens arrays.

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ABSTRACT | Three-dimensional (3-D) imaging techniques have the potential to establish a future mass-market in the fields of entertainment and communications. Integral imaging (InI), which can capture and display true 3-D color images, has been seen as the right technology for 3-D viewing for audiences of more than one person. Due to the advanced degree of its development, InI technology could be ready for massive commercialization in the coming years. This development is the result of a strong research effort performed over the past few years. In this sense, this paper is devoted to reviewing some recent advances in InI, which have allowed improvement in the response of InI systems to the problems of the limited depth of field, poor axial and lateral resolution, pseudoscopic-toorthoscopic conversion, production of 3-D images with continuous relief, or the limited range of viewing angles of InI monitors.

**KEYWORDS** | Depth of field; enlarged viewing angle; 3-D imaging and display

## I. INTRODUCTION

INVITED PAPER

The design and development of techniques for the recording and display of three-dimensional (3-D) scenes has attracted the attention of scientists and engineers in very different disciplines. During eighteenth century, Smith [1] and Porterfield [2] studied the influence of

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binocular vision on the disparity between the images perceived and on depth perception. In the nineteenth century, Wheatstone [3] proposed the first theory on binocular vision and built the first stereoscope. Note, however, that a stereoscope provides with only a single relief perspective of a given scene. Thus, two observers at different locations would perceive the same image.

At the beginning of the twentieth century, Lippmann [4] proposed a novel technique, named integral photography (IP), which allows the reconstruction of true 3-D images. This technique, which is based on the reversibility principle for light rays, is characterized by being autostereoscopic, namely, there is no need for the use of any additional device to perceive the 3-D images. A few years later, Ives [5] proceeded on Lipmann's research and proposed the use of lens sheets and parallax barriers. During the second half of the twentieth century, groups lead by Buckhardt, Okoshi, and McCornick [6]–[9], respectively, continued the study and improvement of the IP design.

The first attempts for obtaining 3-D animated images were severely limited by the microlens arrays technology and the low resolution of the digital cameras and video projectors available in the 1980s. In addition, real-time processing of the required amount of information was unreachable for the devices available by that time. However, thanks to the advances in microlens-array fabrication techniques and also to the development of high-resolution digital methods, nowadays the IP concept has been rescued under the name of integral imaging (InI) [10]. The initial limitations in resolution seem to be gradually overcome by use of successive generations of digital cameras [chargecoupled device (CCD) and complementary metal-oxidesemiconductor (CMOS)] and digital displays. The use of computer processing techniques has extended the InI and its applications to many fields with undiminished intensity. The applications in medicine, telemetry and 3-D object

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recognition are especially remarkable. The InI systems are continuously improving their marks in resolution, processing speed, and memory, decreasing their cost at the same time.

### **II. PRINCIPLES OF INTEGRAL IMAGING**

To understand the principles of integral imaging, it is convenient to start by revisiting the principles of integral photography [4]. In Lippmann's scheme, the photography of a self-luminous 3-D scene is taken through a pinhole array; see Fig. 1(a). This pickup setup provides, at the film plane, a set of equally spaced two-dimensional elemental images, each having information of a different perspective of the object. The second stage of Lippmann's procedure is the display stage, in which the properly processed film is placed in front of the same pinhole array and back-illuminated so that each elemental image works as a spatially incoherent object. Now the rays emitted by the points in the elemental images intersect, as shown in Fig. 1(b), so that the 3-D scene is reconstructed. As illustrated in the figure, a binocular observer will perceive the volume of the scene only if the two eyes receive light from the reconstructed points. Another important question is the fact that this method allows the reconstruction of a real but depth-reversed image of the 3-D scene.

The major drawback of Lippmann's scheme is the extremely poor light efficiency of both the capture and the display stages. To gain some light efficiency, one should



**Fig. 1.** (a) Scheme of pickup and (b) display stages of an integral photography system.



**Fig. 2.** Scheme of (a) pickup and (b) display stages of an integral imaging system.

enlarge the pinhole's size. In such case, one should redraw Fig. 1 but with conical ray bundles instead of single rays. This would produce a strong deterioration of lateral and depth resolution in both stages. The second problem of IP is that the film processing inherent to a photographic process is very slow and therefore does not match the speed requirements of modern 3-D imaging and video.

A solution to these problems is to substitute the pinhole array by an array of microlenses (MLA) and the photographic film by an electronic matrix sensor like a CCD or a CMOS. As shown in Fig. 2, the microlenses allow the acquisition of much more brighter elemental images. However, two new problems arise due to the use of this new technology. On the one hand, the spatial resolution (i.e., the number of pixels) of electronic matrix sensors is still much poorer that that of the classical photographic films. However, the resolution of such devices is continuously improving, and it is expectable that in a short time, it will reach the resolution of films. The second problem is caused by the imaging capacity of microlenses. Due to this capacity, only one plane of the object space (which we will name the reference plane) is in focus, and therefore produces sharp images. The light emitted by points of the object out of this plane does not focus onto the CCD and therefore gives rise to increasingly blurred images.

The same problems happen in the display stage, as illustrated in Fig. 2(b). On the one hand, the poor spatial resolution of the liquid crystal display (LCD) could

compromise the lateral and depth resolution of the reconstructed scene. On the other hand, due to the imaging properties of lenses, only points on the reference plane are reconstructed sharply. Other parts of the reconstructed 3-D scene are increasingly blurred. Consequently, InI systems produce much more luminous and dynamic reconstructions of 3-D scenes but with lower lateral and depth resolution.

# III. THE PICKUP STAGE OF INTEGRAL IMAGING

If we assume that in the future the spatial resolution of electronic matrix sensors will reach that of photographic films, one could forget the limitations connected with the pixelation of elemental images. In such case, the main challenges of InI pickup stage are a) the limited depth of field (DOF); b) the overlapping of elemental images; and c) the limitations in viewing angle. This section is devoted to reviewing some strategies for overcoming such problems.

# A. Hybrid Technique for Extending the Depth of Field

Let us consider the light emitted by (or scattered at) a 3-D object. It is straightforward, by application of paraxial diffraction equations [11], to find that the intensity distribution in the elemental image provided by an arbitrary microlens (for example, the central one), is given by

$$I(\mathbf{x}) = \int R(\mathbf{x}_S) H(\mathbf{x} - M_z \mathbf{x}_S; z_S) d^2 \mathbf{x}_S$$
(1)

where  $\mathbf{x} = (x, y)$  refers to the transverse coordinates at the integral image plane,  $(x_S, y_S, z_S)$  to the coordinates of the source points (measured from the central microlens), and  $M_z$  the magnification factor  $M_z = -g/z_S$ . Function  $R(\mathbf{x})$ accounts for the object reflectance. Note that this equation is not a convolution since the function H depends on the depth position of the source [12]. If we assume that the pupil of each microlens is a circle with diameter  $\phi$ , then the function H can be written in polar coordinates as

$$H(r,z) = \left| \int_{0}^{\phi/2} p(r_o) \exp\left\{\frac{i\pi z r_o^2}{a(a-z)\lambda}\right\} J_o\left(2\pi \frac{rr_o}{\lambda g}\right) r_o dr_o \right|^2.$$
(2)

Note that this function is simply the intensity point-spread function (PSF) of an individual microlens. In this equation, *r* accounts for the radial coordinate  $(r^2 = x^2 + y^2)$  and *a* is the distance between the MLA and the reference plane. As illustrated in Fig. 3, the PSF spreads very fast, with defocus giving rise to very blurred elemental images for out-of-focus points of the 3-D scene.



Fig. 3. The elemental image of a point spreads as defocused.

The trivial way for improving the DOF of pickup stage is by reducing the aperture of the microlenses. However, this is not a practical solution because such an improvement would be accompanied by a proportional deterioration of the lateral resolution. This problem can be overcome by use of either amplitude [12] or phase modulation of microlenses transmittance. Specifically, the insertion of a circular obscuration at the central region of any microlens produces an increasing of the DOF of the MLA and does not induce any significant deterioration of the lateral resolution. The main advantage of this annular parallel apodization of all the microlenses is that elemental PSFs spread very slowly for out-of-focus points, and therefore it is possible to apply deconvolution tools to improve the quality of the elemental-images set.

To illustrate the utility of such hybrid method we show the results of a numerical imaging simulation. In the calculations we considered a MLA with f = 5.0 mm and pitch p = 1.0 mm. As the object for the simulation we selected the spoke target. Four targets were placed at  $z_S = 175$  mm, 109 mm, 92 mm, and 70 mm, from the reference plane, which was set at a = 100 mm. In Fig. 4(a), we show the central elemental image. In Fig. 4(b), we show the same elemental image but obtained after setting the central obscuration, of diameter  $\delta = p/\sqrt{2}$ , and applying a typical Wiener deconvolution algorithm.

Although it is clear that the hybrid procedure results in an enlargement of the DOF, still one question remains: how to implement in a real experiment the parallel apodization? The answer to this question will be addressed next.



Fig. 4. Elemental image obtained with (a) the classical procedure and (b) the hybrid procedure.



Fig. 5. A set of opaque barriers is necessary to avoid the overlapping between elemental images.

#### B. The Telecentric Relay System (TRES)

To understand the problem of the overlapping of elemental images, let us draw again the scheme of InI pickup in Fig. 5(a). Note that this architecture cannot be used for real pickup. One problem is the small size of matrix sensors, which does not match the size of the elemental-images set. The second problem comes from the fact that when capturing large scenes, the elemental images are much larger than the corresponding elemental cells, giving rise to strong overlapping between them. Typical solutions to this problem are the use of GRIN microlenses [15] or the insertion of opaque barriers [16], as shown in the scheme of Fig. 5(b).



Fig. 7. Subset of  $2 \times 2$  elemental images recorded by with the (a) conventional relay and (b) TRES.

The use of a special type of relay system, the TRES, was proposed for overcoming simultaneously, and by purely optical methods, the two problems [17]. As shown in Fig. 6, the conjugate of the aperture stop through the microlenses are the elemental micro entrance pupils (micro-EPs) of the pickup system. The micro-EPs are aligned with the centers of the microlenses. Since only the rays passing through the micro-EPs are captured, the elemental images are cut away so that they match the corresponding elemental cells.

To illustrate the utility of the TRES, we performed a pickup experiment in which the 3-D scene consisted of three plates with the letters R, G, and B printed on them. The system was adjusted so that the letter G was in focus. The axial distances were  $a = z_{\rm G} = 100$  mm,  $z_{\rm B} = 160$  mm, and  $z_{\rm R} = 50$  mm. The parameters of the microlenses were f = 3.3 mm and p = 1.01 mm. With such elements, we captured two sets of elemental images: one with the TRES and the other by using the conventional relay system. A subset of  $2 \times 2$  elemental images is shown in Fig. 7.

In addition, we simulated by computer the reconstruction stage. In Fig. 8, we show one view of the reconstructed image. The view corresponds to the case in which the observer's eye is centered at the optical axis of the central microlens. From the views, it is clear that the TRES allows the reconstruction with better resolution, without distortion in scale, and even with better DOF.

An additional advantage of using the TRES is that it provides a very simple method for implementation of parallel apodization. It is only necessary to insert the amplitude modulator in the plane of the aperture stop (see



Fig. 6. Scheme of the telecentric relay system.



Fig. 8. Reconstructed images calculated from the microimages captured with the (a) conventional relay and (b) TRES.

Fig. 6), so that its conjugate through any microlenses is located just in front of the microlenses.

### C. Optical Method for Enhancement of Viewing Angle

As stated above, one of the main challenges of InI is to overcome the limited viewing angle of InI monitors. This is a very important deficiency because the 3-D images reconstructed with InI systems can be visualized only from a narrow range of angular positions. Some research groups have perceived the importance of this problem and therefore have made interesting suggestions. Among them, the proposal of switching of the elemental lenses [18], the use of curved lens array [19], [20] or the adjustment of viewing windows [21] are remarkable. These techniques, however, do not display simultaneously in all the directions or, in the latter case, are useful only for 3-D scenes in the vicinity of the center of the curved array. Other proposals for achieving some enhancement in the viewing angle consider the use of a 2000-scanning-line video system [22] or the computational synthetic aperture [23].

To understand the reasons for the limitations in viewing angle, we revisit Fig. 5(b), where we see that due to the optical barriers, any point of the object is recorded in only some few elemental images. Consequently, during the display, the image of such point can be seen only through the same few microlenses. This effect determines the viewing angle of InI displays. The viewing angle  $\Omega$  can be calculated as  $\tan(\Omega/2) = p/(2g)$ .

To overcome the problem of viewing-angle limitation in InI monitors, Choi *et al.* suggested a clever method in [24], where they presented the concept of oblique opaque barrier array. If the set of elemental images is captured with oblique barriers, the reconstructed image can be seen from a range of angles different from the one obtained in the perpendicularbarriers case. Choi *et al.* suggested tilting the barrier with enough speed to induce afterimage effect and synchronizing the display of the corresponding elemental images.

The oblique-barriers method can be implemented by a purely optical procedure. Specifically, in [25], a new design of the telecentric relay is proposed for the parallel acquisition of three sets of elemental images. The same system is used for the parallel display of the three sets. The system is named the Multiple-Axis Telecentric Relay System (MATRES).

As shown in Fig. 9, in the MATRES, the camera lens is substituted by an array of three camera lenses, each with the corresponding aperture stop. In this way, the telecentricity condition holds in three directions: the perpendicular one and two oblique directions. The central camera lens acquires the same collection of elemental images as the conventional TRES. The left and the right camera lenses acquire two additional sets of elemental images, each with different, but complementary, perspective information.

Note that the MATRES allows the simultaneous implementation, by optical means, of three sets of perpendicular and oblique barriers. As in Fig. 6, any microlens can



Fig. 9. Scheme of the MATRES. (a) The central camera lens acquires the same elemental images as the TRES. (b) The left and the right cameras acquire two additional sets of elemental images.

form the image of only parts of the object within a cone originated at the corresponding micro EP. But now each microlens has, in parallel, three micro-EPs. In other words, each microlens has associated three complementary cones, which yield to a threefold increase of the FOV of any microlens.

The utility of the MATRES was illustrated, again, through a hybrid experiment in which the pickup was obtained experimentally in the laboratory, but the reconstruction stage was the result of computer processing. Fig. 10 shows the layout of the experimental setup. The MATRES was implemented with only two axes, so that the viewing angle only was doubled. As the 3-D scene, a green die was set at a distance of 60 mm from the MLA. The MLA was composed of  $51 \times 51$  square microlenses of  $1.01 \times 1.01 \text{ mm}^2$  size and focal length of f = 5.0 mm.

The two sets of elemental images obtained with the MATRES are shown in Fig. 11. Some frames of the reconstructed image, which has been calculated assuming a distance of 600 mm from the observer to the MLA, are shown in Fig. 12. The improvement of the viewing angle is apparent.

# IV. THE DISPLAY STAGE OF INTEGRAL IMAGING

As in the pickup, we can start this section by assuming that in the future, the spatial resolution of electronic matrix





Fig. 12. Reconstructed images obtained with (upper row) conventional TRES and (lower row) the MATRES for viewing positions ranging from  $-8.8^{\circ}$  to  $+8.8^{\circ}$ .

Fig. 10. Sketch of the experimental pickup with a two-axis MATRES.

display devices will reach that of photographic films, so that one could forget the limitations connected with the pixelation of elemental images. In such case, three important features of InI monitors are a) the facetted structure of reconstructed images; b) the braiding of facets for objects far from the reference plane; and c) the pseudoscopic to orthoscopic conversion. This section is devoted to analyzing these features and reviewing the different strategies for overcoming the problems connected with such effects.

#### A. Multifacet Structure of Observed Image

When the observer places the eye in front of the MLA and looks through it, he/she sees a different portion of the reconstructed image through any different lenslet. Such image portions are the elemental fields of view (EFOVs) provided by any microlens. Depending on the system geometry, the EFOVs may overlap or may not, giving rise in some cases to reconstructed images divided in multiple facets. Such multifacet structure can degrade the quality of the observed image because it breaks the continuity of its visual aspect. In what follows, we analyze the importance of the multifacet phenomenon and the influence on it of the observer position and the lenslets' fill factor.

In Fig. 13, we show a scheme of the observation of the reconstructed image. In this scheme, we consider the trivial case of reconstruction of a plane object placed at



Fig. 11. Set of  $51 \times 51$  elemental images obtained with (a) the left-hand-side camera lens and (b) the right-hand-side camera lens.

the reference plane. The image is reconstructed by superposition of projected elemental images. The observer is placed at a distance D from the MLA. Take into account that the distance from the observer to the reconstructed image D - a must be larger than the nearest distance of distinct vision, which, for the case of an adult observer, is about 250 mm [26]. As heuristically shown in Fig. 13, the observer's full FOV is composed by a collection of EFOVs arranged in a rectangular grid. Such EFOVs are centered at positions

$$\mathbf{x}_{\mathbf{c}}(\mathbf{m}) = \frac{D-a}{D}\mathbf{m}p \tag{3}$$

where  $\mathbf{m} \in \mathbb{Z}^2$  stands for indexes labeling the lens that provides the corresponding EFOV. Although in the pickup stage, it is preferable for the lenslets to be circular shaped, in the display stage it is much more preferable to proceed with square-shaped lenslets. The EFOVs shape results from the convolution between two projected pupils: a) the projection, through the eye-pupil center, of the lenslet pupil onto the image plane and b) the projection, through



Fig. 13. The observed reconstructed image consists of a rectangular grid of EFOVs.

the lenslet center, of the eye pupil onto the image plane [27]. Then, the EFOVs are expressed as

$$E(\mathbf{x}) = \operatorname{rect}\left(\frac{\mathbf{x}}{w}\right) \otimes \operatorname{circ}\left(2\frac{\mathrm{r}}{\phi_{EFOV}}\right) \tag{4}$$

where

$$\phi_{EFOV} = \frac{a}{D}\phi_{\rm E}$$
 and  $w = \frac{D-a}{D}\Delta_{\rm L}$ . (5)

Here  $\phi_{\rm E}$  is the observer's pupil diameter and  $\Delta_{\rm L}$  the lenslet width. Since the EFOVs are obtained as the result of the convolution between two binary functions, they are no longer binary. Specifically, they consist on a central zone with uniform field of view and an outer zone of vigneting where the illumination falls off gradually. For distances *D* larger than

$$D_{\phi} = a \frac{\phi_{\rm E} + \Delta_{\rm L}}{\Delta_{\rm L}} \tag{6}$$

the eye pupil acts as the exit pupil of the system, whereas the lenslet acts as the exit window. Then the EFOVs have a square-like shape. On the contrary, for  $D < D_{\phi}$ , the eye pupil acts as the exit window, and therefore the EFOVs have a circle-like shape.

The reconstructed image as seen by the observer, i.e., the observed reconstructed image  $ORI(\mathbf{x})$ , is obtained as the linear superposition of the array of EFOVs, that is

$$ORI(\mathbf{x}) = \sum_{\mathbf{m}} \{O_{\mathbf{m}}(\mathbf{x}) E[\mathbf{x} - \mathbf{x}_{\mathbf{c}}(\mathbf{m})]\}$$
(7)

where  $O_{\mathbf{m}}(\mathbf{x})$  is the conjugate at the reference plane of the **m**th elemental image.

To illustrate the importance of faceting effect, we have simulated the reconstruction, according to (3)–(7), of the 3-D scene used in Section III-B. We calculated the observed image for different values of the system parameters; see Fig. 14. We conclude that for an observation with continuous relief, a minimum value of D and fill factor  $\varphi$  equal to one are required. Note, however, that the multifacet effect can be reduced by use of moving array lenslet technique [28], [29].

#### B. The Facet Braiding

Closely connected with the multifacet effect is the phenomenon called facet braiding, which appears in the reconstruction of parts of the scene far from the reference plane [30]. To understand this phenomenon, we start by a scheme of the pickup stage. As shown in Fig. 15, an object



**Fig. 14.** The observed reconstructed image obtained after setting (a) D = 400 mm,  $\phi_E = 10 \text{ mm}$ , and  $\varphi = 1.0$ ; (b) D = 1.0 m,  $\phi_E = 3 \text{ mm}$ , and  $\varphi = 1.0$ ; and (c) D = 1.0 m,  $\phi_E = 3 \text{ mm}$ , and  $\varphi = 0.4$ . In all these cases, a is set to 100 mm.

placed at the reference plane produces a collection of sharp elemental images. In the case of out-of-focus objects, the scale, spacing, and position of the elemental images depend on the distance between the object and the MLA. Of course, the light emanated from out-of-focus points does not focus sharply onto the sensor. We will assume, however, that techniques for DOF enlargement are applied, so that even out-of-focus objects are recorded sharply.

As shown next in Fig. 16, the reconstruction and visualization process is the result of three phenomena: a geometrical projection, an image formation process, and the arrangement of the visual facets. In the case of in-focus objects, a full consonance between the three phenomena occurs, giving rise to a 3-D reconstructed image that is seen



Fig. 15. Scheme of the InI pickup. (a) In-focus scene and (b) out-of-focus scene.

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**Fig. 16.** Display stage. Scenes in the reference plane are seen with continuous relief. Out of the reference plane the visual facets are arranged following a braiding path.

with continuous relief. In the case of out-of-focus objects, the consonance is broken for the following reasons.

- The image is reconstructed with the same position and size as the object.
- ii) The LCD and the reference image plane are still conjugate through the microlenses. Therefore, the images generated by any elemental image through the corresponding microlens do not appear in the same position as the reconstructed image but in the reference plane instead. Although all of these images still have the same size, they appear centered at different positions.
- iii) In the observation stage, the observer sees through each microlens one portion of the image provided by that particular microlens. But now the images provided by the microlenses are displaced so that the visual facets are arranged in a cracked relief. The cracking follows a braiding path.

To illustrate the importance of the facet-braiding phenomenon, we performed an experiment in which we obtained the set of elemental images of a 3-D scene consisting of three capital letters R, G ,and B, each printed on a different plate and located at different distances from the MLA. The InI system was arranged so that the reference plane was set at the G position. Although R and B were clearly out-of-focus scenes, the pickup was arranged so that a high DOF was obtained, and therefore they were recorded sharply (see Fig. 17, where we show three elemental images).

We simulated the display stage by computer processing. In our calculations, we assumed the same MLA as in pickup, and that the observer was placed at a distance D = 400 mm from the MLA. In Fig. 18, we show a view of the reconstructed image. We can clearly see the typical banding that appears in out-of-focus scenes as the consequence of the facet braiding. To solve this problem, we



Fig. 17. Three elements of the same row of the elemental-image set.

propose the use of dynamic focusing technique during the display stage.

The dynamic focusing can be made by using a liquid lens inserted in the aperture stop of the telecentric relay. This allows us to easily implement an array of microzooms and therefore displace the reference plane at will. In the figure, we show the view corresponding to the new reconstruction stage. Note how the dynamic focusing permits the selection of the plane free of facet-braiding effect.

#### C. Pseudoscopic to Orthoscopic Conversion

As is known, in their standard configuration, InI systems provide the observer with real, pseudoscopic images, that is, with a 3-D reconstruction that is reversed in depth. This is a problem that has attracted many research efforts but still has not been conveniently solved, to our knowledge. As we will explain in detail in this section, many different techniques have been proposed to overcome this drawback.

The first attempt to overcome this problem was made by Ives [5], who, in the context of IP, proposed to record a second set of elemental images by using the reconstructed image as the object. When the second set of elemental images is used in a second reconstruction stage, a real, undistorted, orthoscopic 3-D image is reconstructed. This proposal does not constitute an effective solution for the pseudoscopic-orthoscopic (PO) conversion problem. This is because the two-step recording process leads to important image degradation because of diffraction effects and the pixilated structure of the CCD and the LCD [31].

A different approach was suggested by Davies *et al.* [32], who proposed the use of an autocollimating transmission screen placed between the object and the InI microlenses. Although this scheme does not need two recording stages,



Fig. 18. Views of the reconstructed image. (a) The reference plane was set as in the pickup and (b) dynamic focusing was applied.

it still suffers from some drawbacks. On the one hand, the use of the autocollimation screen enhances the detrimental effects of diffraction onto resolution. In addition, the reconstructed image is virtual. However, the formation of a real image of the object is often preferable because such a floating image provides the observer with an impressive feel of depth, since the image appears to be located in the free space near the observer [33].

A very smart and simple scheme was suggested by Okano *et al.* [10]. They proposed to capture the elemental images with the standard pickup architecture. Then, each elemental image was rotated by 180° around the center of the elemental cell. Taking into account the pixilated structure of the elemental images, this operation simply implies a local pixel mapping. As we show in Fig. 19, when these rotated elemental images are displayed at a distance  $g_v = g - 2f^2/(d-f)$  [34], a virtual, undistorted orthoscopic image is obtained at a distance  $d_v = d - 2f$  from the MLA. Some other methods have been proposed for the PO conversion either in transmission architecture [35] or by using microconvex mirrors [36]. Interested readers may refer to [37].

An interesting method for providing real, orthoscopic 3-D images was proposed in [38]. The technique makes use of Ives' PO concept, but the intermediate stage (Display 1 + Pickup 2) is performed by digital procedure. As shown in Fig. 20, the optically acquired set of elemental images (Set 1) has a pixelated structure. The conversion to



Fig. 19. Schematic drawing of the orthoscopic, virtual reconstruction.



Fig. 20. Scheme of the PO digital conversion method.

the second set of elemental images (Set 2) is done by a pixel mapping. Since there is no loss of energy in the digital pickup, we perform the digital Pickup 2 through a virtual pinhole array. This simplifies the process.

As shown in the figure, in Pickup 1, a set of elemental images is optically recorded in the CCD. Each elemental image records a different perspective of the object, and all the pixels of the cell are impressed. When, in Display 1, these elemental images are viewed through the pinhole, a faceting effect occurs: a different portion of the reconstructed image is seen through each microlens. Then, through the upper microlens, the central pinhole only can see the "blue" part of the reconstructed image, which indeed was recorded in the "blue" pixel of the upper microcell. In other words, the blue part of the reconstructed image is stored in pixel 1 of cell 1, that is, in the element  $O_{1,1}$  of Set 1. Here the first index refers to the cell and the second to the pixel in the cell. Similarly, the "black" region of the reconstructed image (as seen by central pinhole) is stored in the element  $O_{2,2}$ , and so on. Then, as we see in the scheme, the collection of pixels that conforms to the central elemental image of Set 2 can be obtained after the mapping  $D_{3,j} = O_{6-j,6-j}$ . A similar process occurs when the reconstructed image is seen through the other pinholes. So, we can straightforwardly conclude that the mapping, known as the smart mapping, which provides Set 2 of elemental images (which will permit, after optical Display 2, the reconstruction of a real, undistorted, orthoscopic image) can be expressed as

$$D_{i,j} = O_{k,\ell} \tag{8}$$

where

$$k = i + \left(\frac{M+1}{2}\right) - j; \text{ and } \ell = (M+1) - j.$$
 (9)

In this equation, we have assumed that the number of microlenses is an odd number. In the case of an even number of lenses, a similar equation holds. If for a given

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value of *j* the corresponding k < 1 or k > M, then the corresponding pixel  $D_{i,j}$  is set to zero.

### **V. CONCLUSION**

We have performed a review of advances in the pickup and display stages for integral imaging. Specifically, we have

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shown that by purely optical techniques, important improvement in depth of field, lateral resolution, viewing angle, and visual quality of reconstructed images can be achieved. Another important advance is the development of easy techniques for the pseudoscopic-to-orthoscopic conversion, or the invention of a very simple technique for implementation of arrays of zoom microlenses. ■

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