Method to Remedy Image Degradations Due to Facet Braiding in 3D Integral-Imaging Monitors

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***Abstract*—One of the main challenges in 3D integral imaging (InI) is to overcome the limited depth of field of displayed 3D images. Although this limitation can be due to many factors, the phenomenon that produces the strongest deterioration of out-of-focus images is the facet braiding. In fact, the facet braiding is an essential problem, since InI 3D monitors are not feasible if the braiding problem is not solved. In this paper, we propose a very simple method for overcoming the facet braiding effect which is a serious limitation for realization of 3D TV based on InI. Hybrid experiments are presented to verify the theoretical analysis.**

***Index Terms*—Depth of field, smooth images, three-dimensional (3D) display.**

I. Introduction

INTEGRAL IMAGING (InI) is a 3D display and visualization technique well suited to provide with 3D images to audiences of more than one person. An InI procedure consists of two stages: capture and display. The capture of the 3D scene is usually done by inserting a microlenses array (MLA) in front of the objective of a digital camera. The system is arranged so that the MLA produces a collection of 2D aerial micro-images (usually named as elemental images) of the 3D scene. Any elemental image stores information of a different perspective of the 3D scene, so that the 3D information is codified in the collection of 2D elemental images. Finally, the camera objective images the elemental images onto the matrix sensor (typically, a charge-coupled device a (CCD) or a CMOS) which records the collection of elemental images (also named as the integral image). Naturally, the resolution and depth of field with which the integral image is recorded depends on many factors such as the number of microlenses, the number of pixels, or the f-number of the objective [1]. We need to take into account, however, that a large number of pixels may not be feasible because this severely increases the amount of data.

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Naturally, the use of a MLA is not the only method of collecting the elemental images. There are a number of other possibilities to pick up perspective images and/or to use a computer to create the integral images corresponding to the 3D scene (see, for example, [2]–[4]) In case of large 3D scenes, it may be preferable to use an array of digital cameras [2]. When the acquisition speed is not an issue, it is possible to use only one camera that is mechanically translated following a path [3].

In the optical reconstruction stage, the recorded images are displayed by a matrix display device, such as a LCD or OLED monitor, placed in front of another MLA. Another possibility is the use of a digital projector to project the elemental images onto a diffuser placed in front of the MLA [5]. In any case, the ray-cones emitted by the pixels of the matrix display follow the same path as in the pickup, but in the opposite direction; therefore, they intersect with high density in the same positions as the original points of the 3D scene. This 3D imaging system is said to be auto stereoscopic, because the observer can perceive the 3D scene without the help of any additional viewing device, such as special glasses. Advantages of InI over other auto-stereoscopic techniques are the fact that InI offers not only horizontal, but also vertical parallax, and that the parallax is almost continuous over the viewing angle.

InI principles were first proposed by Lippmann [6]. under the name of integral photography, and some relevant work was done in the meantime [7]–[11]. However, the interest in InI was lethargic due to the limited applications achievable with the technology available by that time. This interest was resurrected about one decade ago for its application to 3D TV and display [12].

Since its rebirth, InI has overcome many of its challenges. It is remarkable, for example, that a number of techniques for the pseudoscopic to orthoscopic conversion were developed [13]–[15]. Some methods were proposed to overcome the limits in lateral resolution imposed by the pixelated structure of the CCD [16]–[18], or by the microlens array [19], [20]. Another challenge faced is the enhancement of the depth of field (DOF) [21], [22] of elemental images obtained in the pickup stage. Other approaches to multi view display have been reviewed in [23]–[26].

However, still more work is required to solve the problem of the poor DOF in the display stage. It has been recognized that facet braiding constitutes one of the essential limitations of DOF of InI monitors [27]. In particular, it was shown that the braiding appears due to the conflict between the focusing capacity of microlenses and the necessity of ray-cones intersection for the optical reconstruction of 3D images. As result, the images of out

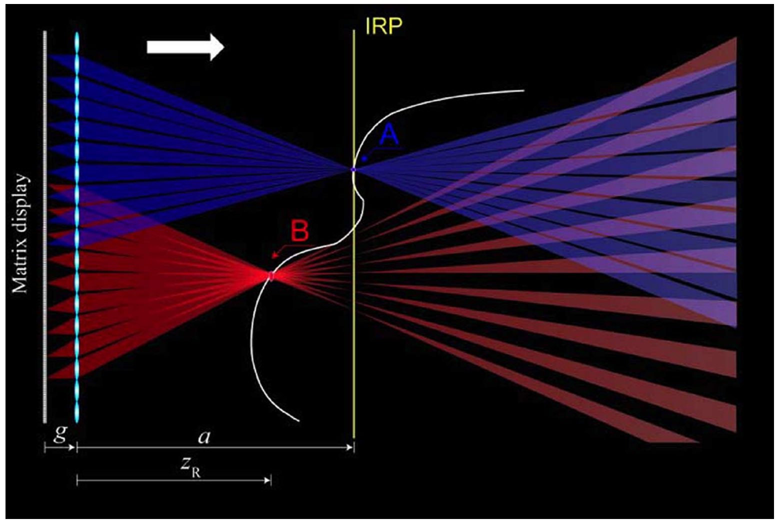

Fig. 1. Illustrating the DOF limitation in InI display.

of focus planes are observed with increasing degradations (similar to spatially cracked images). This heterogeneous quality of observed 3D images is unacceptable for monitors' users. In this paper, we propose an approach to overcome this problem. Our proposal is simple and does not alter other capacities of InI monitors. Specifically, we propose to arrange the InI monitors so that the gap between the elemental images and the MLA is set equal to the focal length of the microlenses. This adjustment allows removing the reference plane from the 3D-scene neighborhood; and therefore it allows avoiding the conflict between the imaging capacity of microlenses, and the light-cones intersection inherent to the scene reconstructions.

To illustrate our proposal, we have performed hybrid experiments in which the elemental images of a 3D scene are obtained in the laboratory, but the process of reconstruction and visualization has been simulated with a computer.

The paper is organized as follows. Section II is devoted to a review of the limitation of DOF in InI display. In Section III, we revisit the concept of facet braiding, and perform a hybrid experiment to illustrate its importance. Section IV presents our method for overcoming the facet braiding. Finally, in Section V we outline the main achievements of this work.

II. Basic Theory

As stated above, although InI systems can be used for many interesting purposes, their primary application is the implementation of flat monitors for the display, with full parallax, of 3D auto-stereoscopic images. In other words, for the display of 3D images that can be observed directly without the help of any additional device, like special glasses. When the watcher is observing a 3D scene through a monitor, it is very convenient the DOF of the reconstructed 3D scene be of the same order of magnitude as the DOF of the ocular system. Unfortunately, in current realizations of InI the DOF of reconstructed images is much smaller due to some factors.

As described in [28]–[30] there are, basically, two kind of projection types according to the gap between the matrix display device and the MLA. One is the depth-priority InI (DPII) regime and the other the resolution-priority InI (RPII) regime. In the DPII the gap is equal to the focal length of the microlenses. DPII monitors have good depth of field, but poor lateral resolution, which is determined by the pitch of the MLA. In the RPII the gap is slightly different from the microlenses focal length. In such case there exist a privileged plane in the reconstruction space, the so-called the image reference plane (IRP), which is conjugate with the display device. As shown in the Fig. 1, in such plane the images are reconstructed with very good resolution (see point A in the figure). Points that do not belong to the reference plane are reconstructed with worse resolution. This is because, in such cases, the ray-cones emerging the microlenses still converge at the reference plane, but intersect at the position of the points (see point B), where the cones have spread. The resolution of reconstructed images is still better than in the DPII over a long range of depth distances. Out from this depth range the lateral resolution is worse than in the DPII.

To be more explicit, we can make some easy calculations concerning the lateral resolution of reconstructed images in the RPII regime. If we take into account the pixilated structure of the matrix display, then the resolution limit at the reference plane is

$$\Delta_{\rm a} = \Delta_{\rm x} \frac{a}{g} \tag{1}$$

where $\Delta_{\rm x}$ denotes the display pixel size. At a plane placed at a distance $Z_{\rm R}$ from the microlenses, the images are reconstructed with resolution

$$\Delta_{\rm z} = \Delta_{\rm x} \frac{z_{\rm R}}{g} + p \frac{|z_{\rm R} - a|}{a} \tag{2}$$

where p stands for the pitch of the MLA.

Both well known and evident from (2), the natural method for improving the DOF of InI display stage, i.e., the method of reducing the blurring of images reconstructed in planes far from the reference plane is based on increasing the number of pixels of the matrix display and on reducing the MLA pitch. Note however that the pitch cannot be reduced indefinitely, since

Fig. 2. Illustrating the braiding effect for point objects. Obviously the scale of the figure is distorted; in a real case the distance between the replicas is much more smaller.

small lens apertures can produce much more blurring due to diffraction effects [31], [32].

III. The Facet Braiding Effect

If we look again at the RPII display setup shown in Fig. 1, we can wonder what an observer sees when looking through the MLA. When answering this question, it is important to note that the natural trend of the visual system is to adjust the accommodation of the eyes so that sharp images are focused on the retina. This implies that although only point A is reconstructed sharply at the IRP (since point B is reconstructed blurred at a distance z_R), the natural trend of the visual system is to fix the accommodation to the IRP. In such a case, the observer will not see the sharp A and the blurred B. Instead the observer will see a highly luminous, sharp point A and a series of less luminous, sharp replicas of B (see Fig. 2).

This produces a very uncomfortable visual effect to the observer, since he/she does not see blurred images of out-of-focus points, but multiple sharp replicas. The problem gets worse when we consider the observation of reconstructed images of bigger objects, as we show next.

As we show in the Fig. 3, scenes out from the reference plane (like point B in Fig. 1) are observed with cracked relief. This is due to the following facts. 1) All the ray-cones emanated from the microlenses intersect constructively at the object plane (also named as the reconstruction plane) to give an image that is reconstructed with the same position and size as the original object. Due to the size of the cones, in this case the image is reconstructed with significant blur (see Fig. 3(a). 2) Since the reference plane is the still the conjugate with the matrix display, a series of sharp images of the object (each provided by one microlens) will appear on it. All these images have the same size (which is different from the size of the original object) but are displaced to each other so that they do not match [see the reference plane in Fig. 3(a)]. Finally, 3) in the observation stage, the observer sees through any microlens the corresponding facet. But since the images provided by the microlenses are displaced, the facets are arranged in cracked relief. The cracking follows a

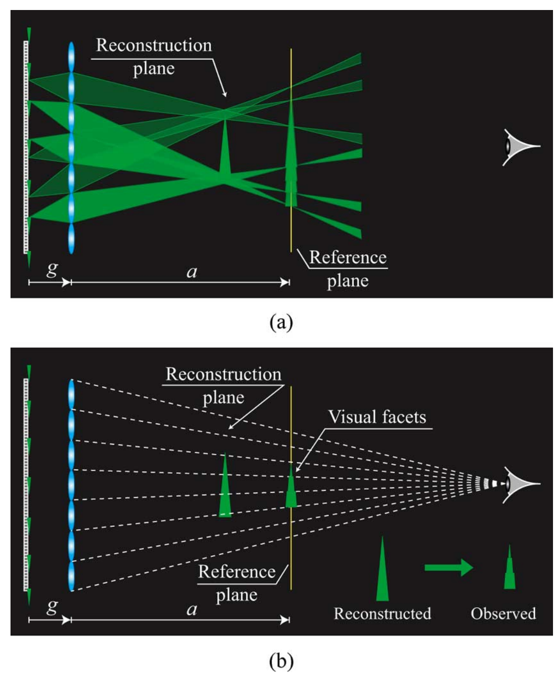

Fig. 3. (a) Scheme of reconstruction of scenes in the reference plane. (b) Observation of the reconstructed scene.

braiding path, which is inverse for objects between the MLA and the reference plane [this is the example represented in Fig. 3(b)], and direct for objects further than the reference plane.

From practical point of view the braiding is the phenomenon that most restrict the DOF of InI monitors, since any part of the scene out from the reference plane is observed, not with increasing blur, but sharp and cracked.

To show the magnitude of the braiding effect we have performed the following InI experiment. On the optical table we prepared, over a black background, a 3D scene composed by an optometrist doll, a tree and a Lego® house. The transverse dimension of the scene was of about 30 cm, while the axial depth was of about 20 cm (see Fig. 4).

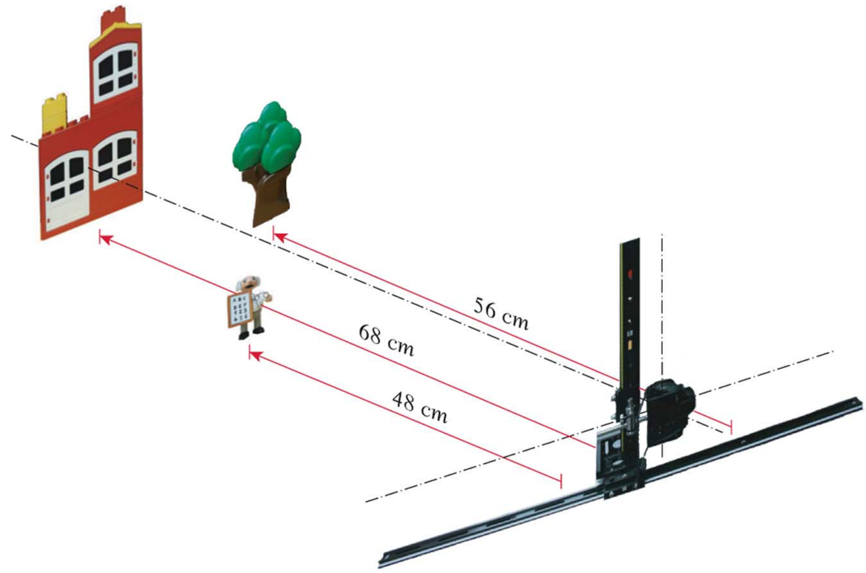

Fig. 4. Scheme of the experimental set up for the acquisition of the set of elemental images of a 3D scene.

Fig. 5. Examples of two elemental images in the same row.

For the acquisition of the elemental images, instead of using an array of digital cameras, we used the so-called synthetic aperture method [3], in which all the elemental images are picked up with only one digital camera that is mechanically translated. The digital camera was focused on the tree. The camera parameters were fixed to focal length $f = 50$ mm and $f_{/\#} = 3.5$. The depth of field was big enough to allow to obtain pictures were the images of all the objects of the 3D scene were sharp. We obtained a set of 41 H×21 V images with pitch $P = 10$ mm. Since the size of the CMOS sensor was 22.2 mm×14.8 mm, we cropped any elemental image in order to remove the outer parts. By this way we could compose the integral image which consisted on 41 H×21 V elemental images of 10×10 mm and 1972×1972 px each.

The reconstruction/visualization stage was simulated in the computer following the next protocol. First, to consider a realistic display situation, the calculations were performed considering a display MLA of pitch $p = 1.0$ mm and focal length $f = 5.0$ mm, and a matrix display with pixel size 40×40 μm. Thus the elemental images were resized to 25×25 px. In Fig. 5 we show two elemental images.

The gap was fixed to $g = 5.58$ mm so that the reference plane was set at $a = 48$ mm, that is, at the position of the optometrist doll. Finally, the observer eye was placed in front of the MLA, at a distance $D = 0.50$ m. The eye entrance pupil diameter was assumed equal to 2.4 mm. In Fig. 6, we show the reconstructed scene as seen by the observer when his/her eye focuses at the optometrist plane (see Appendix).

Fig. 6. Two perspectives of the reconstructed scene, as seen by an observed placed in front the MLA, at a distance $D = 0.50$.

Note that all parts of the 3D scene are in-focus. There is no any blur along the whole scene and, for example, the border of the house is observed with the same sharpness as the optometrist's trousers. However the DOF of this reconstruction is very poor since planes out from the reference plane are observed with big braiding. This braiding is especially apparent in the house, were we observe typical direct braiding in the windows, in the door, and in the chimney.

This kind of cracking of visualized scenes is unacceptable if one want to implement a 3D monitor, since one observer cannot accept this cracking which is not the visual sensation one expect when seen defocused images. It is fairly clear that the facet braiding is the factor that really limits the effective DOF of InI monitors.

IV. Efficient Solution to the Braiding Effect

The facet braiding effect appears due to the conflict between the imaging capacity of lenses, and the ray-cone intersection nature of reconstructed images. Thus, the easiest mode of avoiding

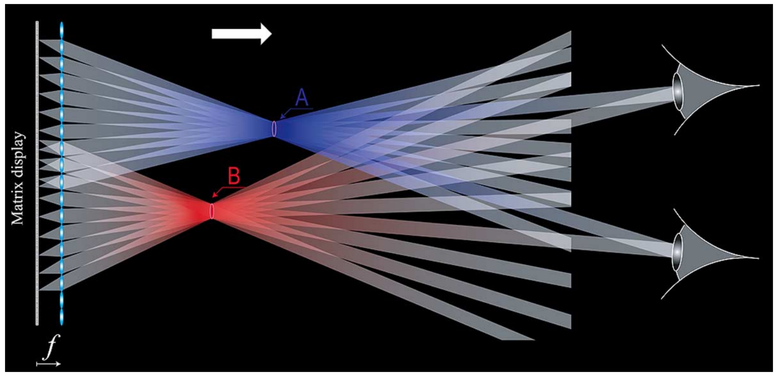

Fig. 7. Scheme of reconstruction of scenes in the DPII mode. Since there is no plane where the beams focus, there is no braiding in the reconstruction.

such conflict is to eliminate one of those phenomena from the InI display/visualization process. What we propose then is to set the matrix display at a distance $g = f$ from the MLA for the reconstruction. By this way we make sure that there is no any privileged plane in the area of reconstruction. Fig. 7 illustrates that when working in this mode (that is, the DPII mode) there is no plane where ray-beams emerging from the microlenses are focused.

It is commonly thought that the DPII mode sacrifices the lateral resolution of reconstructed images, which now is given by

$$\Delta_{\mathrm{z}} = \Delta_{\mathrm{x}} \frac{z_{\mathrm{R}}}{g} + p. \tag{3}$$

However, when comparing (3) with (2), we see that of course in the neighborhood of the IRP the DPII produces worse resolution than RPII. This is because when one works with realistic pixel sizes this difference in resolution is not too significant.

What is very important, however, is the fact that the DPII mode not only reproduces images with homogeneous resolution, but mainly free of braiding whatever the plane was the observer focuses his/her eye.

To support our theory, we have performed a new numerical evaluation of the reconstruction/visualization process. For the calculations we have used, again, the same collection of elemental images as in the previous section. In the simulation the 41 H×21 V elemental images of 25×25 px each were set at a distance $g = 5.0$ mm of the MLA. Again the observer was placed at a distance $D = 0.5$ m from the MLA and focused his/her eye at the optometrist plane. In Fig. 8, we show the reconstructed scene as seen by the observer from two different perspectives.

As apparent from the figure, the facet braiding has disappeared and the resolution is fairly the same over the entire 3D scene. Note that although the image of the optometrist is slightly more blurred here than in Fig. 5, the other parts of the scene are observed with the same resolution, and without the unacceptable cracking.

Fig. 8. Two perspectives of the scene reconstructed in DPII mode as seen by an observer.

V. Conclusion

We have proposed a simple method for avoiding a detrimental effect in the display stage of integral imaging systems. We refer to the facet braiding phenomenon, which appears as result of the conflict between the imaging capacity of the microlenses, and the ray-beam intersection nature of the scene reconstruction. Contrarily to what it was stated in the conclusions of [27]. our solution consists, simply in setting the gap between the micro lenses and the sensor so that the matrix sensor is in conjugate with infinity known as DPII display mode. Note that although DPII is a well known technique; up to now the common thought is that depending on the system requirement (resolution or depth of field) one can select either DPII or RPII. We have demonstrated here, however, that if one want to overcome the braiding which is essential for building practical InI monitors, it is necessary to work in the DPII regime. The resolution priority (RPII) mode may not be an acceptable option.

We have performed hybrid experiments in which the elemental images were captured in the laboratory, but the reconstruction process was simulated with the computer. Our experiments have demonstrated that it is possible to reconstruct 3D scenes without braiding and also without significant loss of resolution.

Appendix

For the calculation of the reconstructed scene as seen by the observer when his/her eye focuses at a given plane we proceeded by using a refined version of the backprojection algorithm [4]. Our algorithm is implemented as illustrated in Fig. 9. First, one

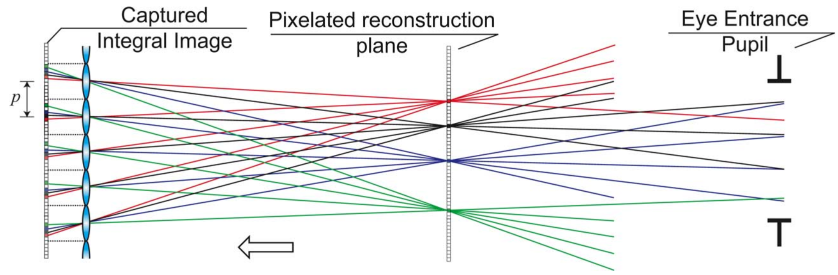

Fig. 9. Scheme to illustrate the reconstruction/visualization algorithm.

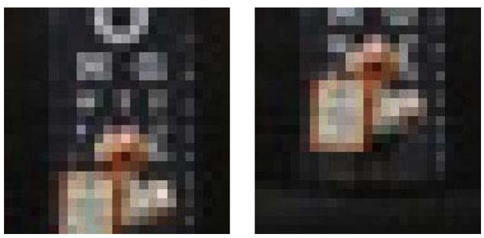

Fig. 10. Two elemental images of the same column.

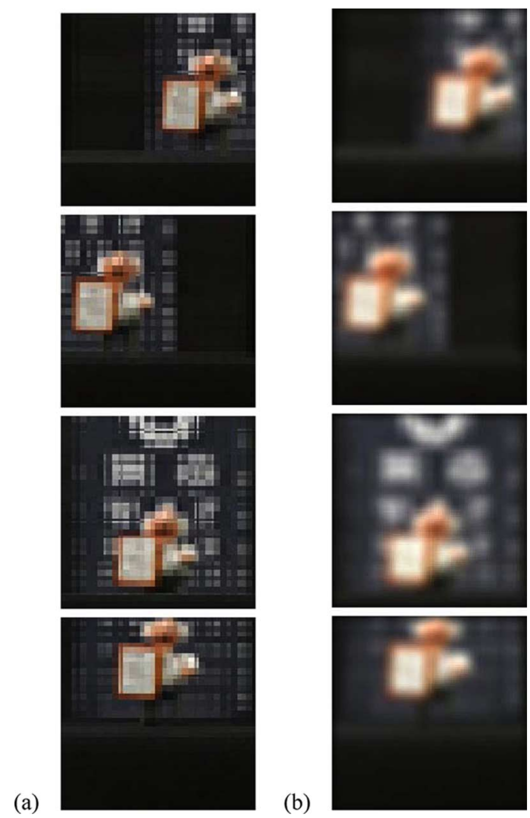

Fig. 11. Four different views, as seen by an observer, of the reconstructed 3D scene displayed with: (a) RPII setup and (b) DPII setup.

selects the plane where the observer focuses his/her eye. Since such plane is conjugate with the retina, one simply has to apply the reconstruction algorithm to such plane, but computing only the rays passing through the eye entrance pupil.

Next, one has to select the size and number of pixels of the reconstructed image. One good selection is to fix the size of the image equal to the lens array size, and the number of pixels equal to that of the integral image. Then, the intensity value at any pixel is obtained by summing up the values of the pixels from the elemental images that are impacted by the straight lines (or light rays) defined by the pixel from the reconstruction plane, and the center of the corresponding microlens. Naturally, this process has to take into account two important facts: one is that only rays passing through the eye entrance pupil are computed; other is that the optical barriers between elemental images limit the number of impacts.

Obtained such intermediate image, the next step is to perform the proper convolution which will make the difference between the RPII image and the DPII one. In the RPII the intermediate image has to be convolved with the projection of a pixel of the integral image; that is, with a square of side Δ_a, as defined in (1).

In the DPII case we have to take into account not only the projection of the pixels, but also the fact that any point from the integral image generates cylindrical ray bundles of diameter p. Then the intermediate image has to be convolved with the function obtained after the convolution between a square of side $\Delta = \Delta_{\mathrm{x}} a/f$, and a circle of diameter p.

To illustrate the method with a second experiment, we obtained, using again the synthetic aperture method, elemental images of a new 3D scene. This new scene was composed by two resolution charts placed a different depths.

In this second experiment, the charts were placed at distances 36.8 and 59.3 cm from the camera. The depth of field of the camera was big enough to allow obtaining sharp pictures of all the objects of the 3D scene. We obtained then a set of 13 H$\times$13 V images with pitch $P = 10$ mm. Again, the data were scaled to realistic display situation, where the MLA pitch $p = 1.0$ mm and focal length $f = 5.0$ mm. The elemental images resized to 25$\times$25 px. In Fig. 10 we show two of such images.

Finally, in Fig. 11 we show four perspectives of the scene as seen by the observer when the display system is set in RPII mode and in the DPII mode. For the calculations the eye entrance pupil diameter was assumed equal to 2.4 mm, the accommodation was fixed at the plane of the optometrist chart (where was set the reference plane in the RPII mode). The coordinates (x, y, z) (measured in mm and with origin in the center of the central microlens) of the center of the eye pupil were, respectively, $(-40, 0, 500)$, $(40, 0, 500)$, $(0, 48, 500)$, and $(0, -37, 500)$.

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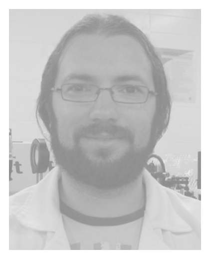

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Dr. Javidi is Fellow of seven scientific societies, including Institute of Electrical and Electronics Engineers (IEEE), American Institute for Medical and Biological Engineering, Optical Society of America, and Institute of Physics. In 2008, he received a Fellow award by John Simon Guggenheim Foundation. In 2010, he was the recipient of George Washington University's Distinguished Alumni Scholar Award, University's highest honor for its alumni in all disciplines. He received the 2008 IEEE Donald G. Fink prized paper award among all (over 180) IEEE Transactions/Journals, and Magazines. In 2007, The Alexander von Humboldt Foundation awarded him the Humboldt Prize for outstanding U.S. scholars. In 2005, he received the Dennis Gabor Award in DiffractiveWave Technologies from the International Society for Optical Engineering (SPIE). Early in his career, the National Science Foundation named him a Presidential Young Investigator, and he received The Engineering Foundation and the Institute of Electrical and Electronics Engineers Faculty Initiation Award. He was the recipient of the IEEE Lasers and Electro-optics Society Distinguished Lecturer Award twice in 2003–2004, and 2004–2005. Early in his career, the National Science Foundation named him a Presidential Young Investigator. He was selected in 2003 as one of the nations top 160 engineers between the ages of 30–45 by the National Academy of Engineering to be an invited speaker at The Frontiers of Engineering Conference. He is on the Editorial Board of the PROCEEDINGS OF THE IEEE (ranked #1 among all IEEE Journals and Transactions), and is currently the Editor in Chief of the Springer-Verlag series on *Advanced Science and Technologies for Security Applications*. He is on the editorial board of the IEEE/OSA JOURNAL OF DISPLAY TECHNOLOGY and SPIE's *Optics Review Journal*.