3D integral imaging with optical processing

Manuel Martínez-Corral, Raúl Martínez-Cuenca, Genaro Saavedra, and Bahram Javidi[+]
Department of Optics, University of Valencia, E-46100 Burjassot, Spain.
[+] Electrical and Computer Engineering Dept, University of Connecticut, Storrs, CT 06269-1157

ABSTRACT

Integral imaging (InI) systems are imaging devices that provide auto-stereoscopic images of 3D intensity objects. Since the birth of this new technology, InI systems have faced satisfactorily many of their initial drawbacks. Basically, two kind of procedures have been used: digital and optical procedures. The "3D Imaging and Display Group" at the University of Valencia, with the essential collaboration of Prof. Javidi, has centered its efforts in the 3D InI with optical processing. Among other achievements, our Group has proposed the annular amplitude modulation for enlargement of the depth of field, dynamic focusing for reduction of the facet-braiding effect, or the TRES and MATRES devices to enlarge the viewing angle.

Key words: Integral imaging, 3D imaging display, optical processing

1. INTRODUCTION

One of the challenges of information society is the development, and subsequent broad implantation, of technologies for acquisition and display of three-dimensional (3D) pictures and movies. The search the optimum 3D imaging/display technique has been the aim of research efforts for long time [1]. However, only in the past few years has the technology reached the level required for the realization of such kind of systems. Among the existing 3D imaging techniques the one known as integral imaging (InI) is especially appreciated because it has the ability of providing real or virtual autostereoscopic intensity images with full parallax, without the help of any special glasses. In an InI system the perspective information of a 3D scene is stored in a collection of 2D images, called elemental images, usually arranged in rectangular grid. The main advantage of an InI monitor is the fact that one observer can see different perspectives of a 3D scene by simply varying the head position [2].

InI was first proposed by Lipmann about one century ago [3]. The interest in InI resurrected recently because of its application to 3D TV [4]. Based on an attractive concept, the first designs of InI systems suffered from many troubles. From that time, much research has been addressed to tackle, satisfactorily in many cases, such troubles. Let us remark for example, the efforts done for improving the lateral resolution [5-7], for enhancing the depth of field [8,11], for pseudoscopic to orthoscopic conversion, or for minimizing the elemental-image overlap [12,13]. InI system have shown to be useful not only for pure 3D imaging but also for other applications like object recognition [14] or the mapping of 3D polarization distributions [15].

Although our group has been working in the field of InI only for the last five years it should be recognized that we have already made some interesting contributions, which help to deal satisfactorily with some of the main challenges of such 3D imaging recording/display system. This paper is devoted to review these achievements.

2. PRINCIPLES OF INTEGRAL IMAGING

In Lipmann scheme, a photography of a self-luminous 3D scene is taken through a pinhole array (see Fig.1(a)). This pickup setup provides with a set of micro-images, named hereafter to as the elemental images, each having information of a different perspective of the object. In the display stage (Fig. 1(b)), the properly processed film is placed in front of the same pinhole array and back illuminated so that each elemental image acts as a spatially incoherent object. As shown in the figure this setup allows the reconstruction of a real, but depth-reversed image of the 3D scene.

The major drawback of the scheme proposed by Lipmann is the poor light efficiency, the second problem is that the film processing inherent to a photographic process is very slow and does not match the current requirements of 3D imaging. A solution of these problems is to substitute the pinhole array by a microlens array and the photographic film by an electronic matrix sensor like a CCD or a CMOS. As shown in Fig. 2, now the elemental images are formed in the image plane of the microlenses. However, now an important problem appears: the limitation in DOF. Due to the imaging properties of the lenses, now only one plane of the object space is in focus. Then light proceeding from other planes does not focus onto the CCD. The same problem happens in the display stage. Only points within the object plane are

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reconstructed sharply. Other parts of the 3D scene are increasingly blurred. Besides, this blurring effect is more significant when the pixilation of the CCD (or the LCD in the display stage) is taken into account. Consequently, this new realization of the integral imaging process gives rise to much more luminous reconstructed images, but with low resolution even in case of the in-focus plane.

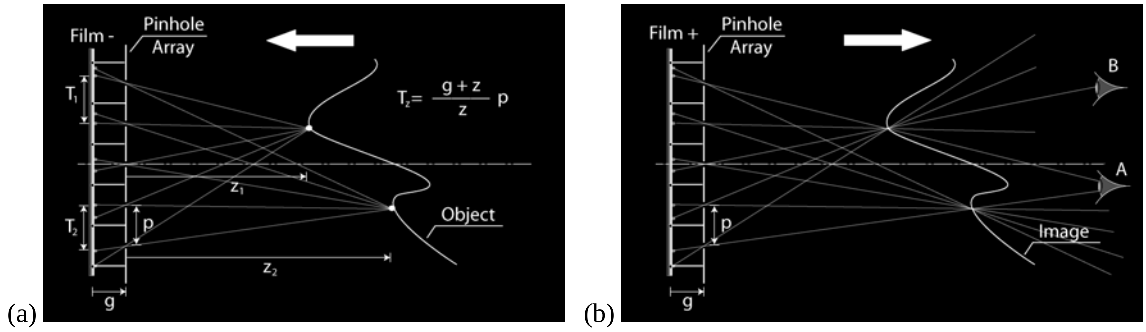


Figure 1.- Scheme of the integral photography method proposed by Lipmann.

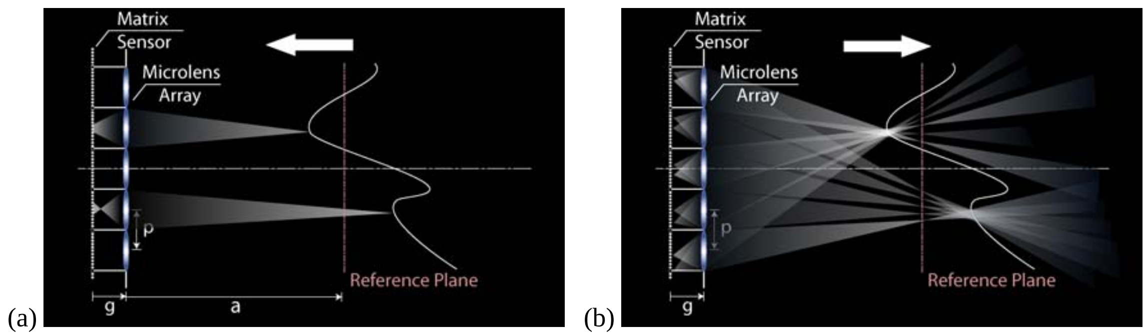


Figure 2.- Scheme of an integral imaging system

Note however that this architecture cannot be used for an actual pickup. This is because when capturing large scenes, the elemental images are much larger than the corresponding elemental cells, giving rise to a strong overlapping between elemental images. In such case, any elemental cell receives light from many microlenses and therefore no useful information can be extracted from them. Typical solutions to this problem are the use an array of GRIN microlenses [16], or the insertion of opaque barriers, commonly known as optical barriers, [17].

3. CORRECTION OF MICROIMAGES OVERLAP AND SHIFT

The use of a relay system was proposed for solving the scale problem. But, additionally, the relay system provides a partial solution to the overlapping problem. To show this, let us focus our attention on Fig. 3 were we have schematized the relay system by means of a converging lens, the relay lens, and the aperture stop. In this layout the ray bundles are shown in color and correspond to an arbitrary microlens. We restrict, at this stage, our analysis to the field of at least one-half illumination. The bounding rays for such field are rays that pass through the center of the relay-system aperture stop and the pickup-system entrance window, which in this case is just the microlens. As we see, due to the presence of the relay system, now the microlenses no longer provide the image of the whole object scene, but the field of view is limited to a smaller region to which we refer to hereafter as micro-vignette. However, these micro-vignettes do not match the corresponding elemental cells, but are smaller and shifted towards the optical axis of the macro. These differences in position and size will produce important image distortion in the reconstruction stage. Besides, the micro-vignettes are not sharply separated. To show this one has to consider the total field of view, which is defined by the bounding rays passing through the top edges of the microlens and the relay-system aperture stop (see bright gray ray bundles in Fig. 3). We find now an important overlapping between neighbor micro-vignettes. This overlapping effect will impoverish the resolution in the reconstructed 3D image.

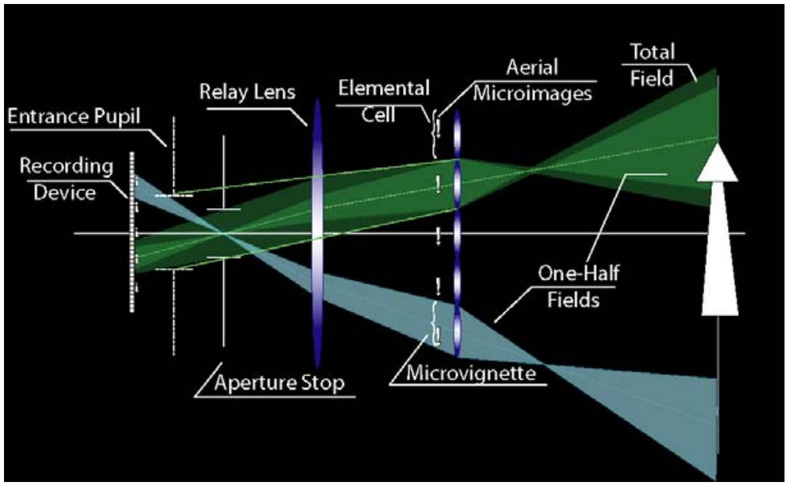


Fig. 3 Scheme of conventional pickup stage of an InI. The relay optics allows the acquisition of higher number of microimages. The microimages size and position is determined by the vignetting effect.

In order to obtain high-quality 3D reconstructions, the pickup process must be optimized. Thus a pickup architecture that provides a collection of non-overlapped microimages whose size and position match the elemental-cell grid is needed. To obtain this one should realize that: (a) the center of each micro-vignette is located just at the intersection of the aerial-images plane and the line joining the center of the microlens with the center of the relay-system entrance pupil (EP); and (b) the extension of each micro-vignette is determined by joining the center of the relay-system EP with the borders of the corresponding microlens. Therefore, to allow the micro-vignettes collection to match the elemental-cells grid, a relay system where the EP is placed at infinity is needed. Besides, the conjugate of this EP through the different microlenses, which will be called micro-EPs, must be small enough to avoid the overlapping effect. In other words, the relay system must be telecentric in its object space [18] and with an aperture stop such that the corresponding micro-EPs are small enough to minimize the overlapping. We will call this setup hereafter with the acronym TRES (which corresponds to Telecentric RElay System) [19]. One must take into account, in the implementation of the TRES, that when the micro-EPs are too small diffraction effects appear which impoverish the lateral resolution of the system. Thus, the proper selection of the aperture stop diameter should be the result of the trade-off between the overlapping effect and the diffraction limit.

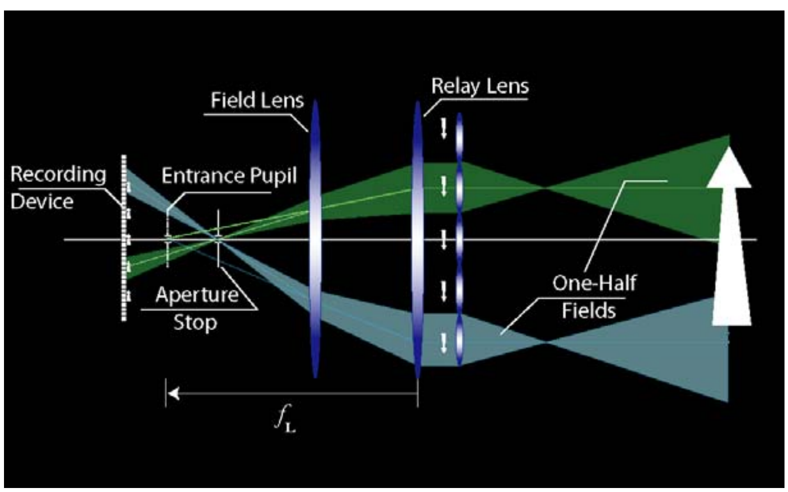


Fig. 4 Scheme of proposed pickup stage. The telecentric relay system allows the micro-vignettes to match the elemental-cells grid.

On the basis of the above reasoning, we propose a new architecture for the pickup stage. Our proposal is schematized in Fig. 4. The relay system is composed of a high-diameter converging lens, the field lens, and a macro objective, which as in Fig. 3 is schematized by the relay lens and the aperture stop. The macro and the field lens should be arranged so that the relay system is telecentric. As shown in the figure, this system permits the capture of a collection of micro-images that match the elemental-cell grid. In other words, this setup permits the acquisition, by optical means, of the correct elemental-image collection.

To confirm the utility of our approach we realized hybrid experiments in which the pickup was obtained experimentally in the laboratory, but the reconstruction stage was the result of a computer processing [20]. In Fig. 5 we show the layout of the experimental setup. The 3D scene used in our experiment consisted of three capital letters, namely *R*, *G* and *B*, each printed on a different plate, located at different distances from the microlens array. As pointed out in the figure, the system was adjusted so that the letter *G* was in focus. We added a double-line square surrounding each target to make the focusing task easier. The size of the letters was set so that they provide micro-images with the same resolution.

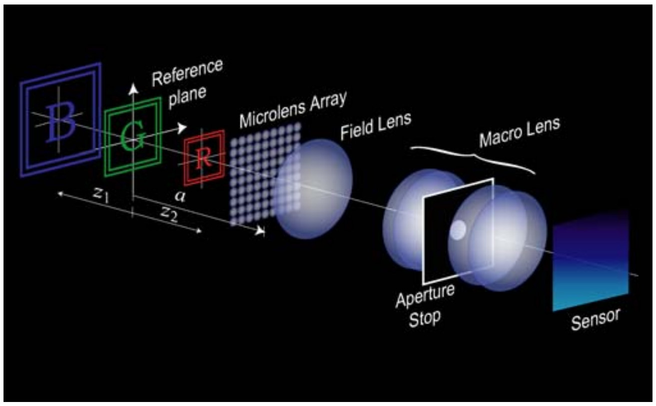


Fig. 5 Experimental setup. The axial distances are a=100 mm, z_1=-60 mm and z_2=50 mm.

We have simulated the display stage in Fig. 6. In our calculations we assumed that an observer is at a distance D=400 mm from the microlens array. We have simulated the display with the microimages recorded with the telecentric, left-hand movie, and the conventional, right-hand one, relay. It is apparent that our setup produces reconstructed 3D scenes with much better resolution, without distortions in scale, and even with better depth of field.

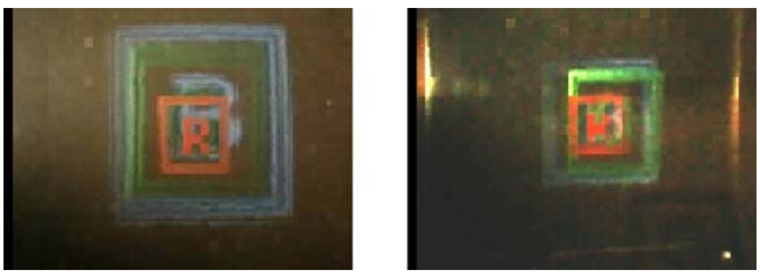


Fig. 6 Virtual, orthoscopic reconstructed images calculated from the microimages captured with the telecentric pickup (left picture) and with the conventional pickup (right picture).

4. ENHANCED VIEWING-ANGLE BY MULTIPLE-AXIS TELECENTRIC RELAY SYSTEM

The use of the TRES in the display stage prevents from the typical flipping effect that appears when an elemental image is seen through the neighboring microlens. The rays have the same trajectory as in the pickup, but in the reverse direction. The image of any point on the 3D object is reconstructed by the intersection of rays emanated from the elemental images in which such point was recorded. Due to the optical barriers any point of the object is recorded in only a 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, Ω, can be calculated as $\tan\Omega = p/(2f)$, where p and f are the pitch and the focal length of the MLA, respectively

To overcome the problem of the viewing-angle limitation in InI monitors, Choi et al. suggested a clever method in Ref. [21], where they presented the concept of oblique opaque barrier array. When the set of elemental images is captured with perpendicular barriers, the reconstructed image of any point of the object can be seen from positions within the cone of angle Ω. 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 perpendicular-barriers case. Thus, if one could capture the three sets of elemental images and display them simultaneously, with three different barrier arrangements, the viewing angle could be expanded by factor three. To do that, Choi et al., suggested tilting the barrier with enough speed to induce afterimage effect, and synchronizing the display of the corresponding elemental images.

(a) (b)

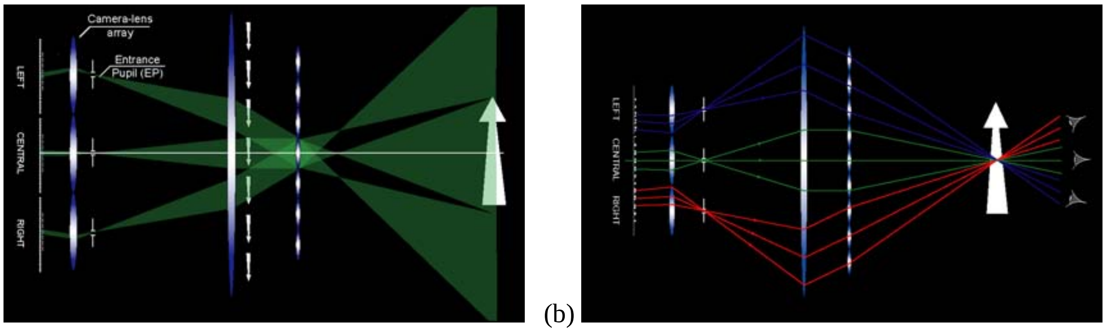


Fig. 7 Illustration of the MATRES. (a) The telecentricity condition holds in three directions; (b) 3D display with MATRES enlarges the viewing angle by a factor of three. As in the pickup, the micro-EPs are the conjugate of the aperture stops through the field lens.

What we have proposed [22] is a new design of the telecentric relay for the parallel acquisition, by optical means, of the three sets of elemental images. The same system is used for the parallel display of the three sets. We named the proposed optical architecture as the Multiple-Axis Telecentric RElay System (MATRES). As we show in Fig. 7(a), 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 is accomplished in three directions; the perpendicular one and two oblique directions. The central camera lens acquires the same collection of elemental images as with 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 shown in Fig. 7(b), any microlens can 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.

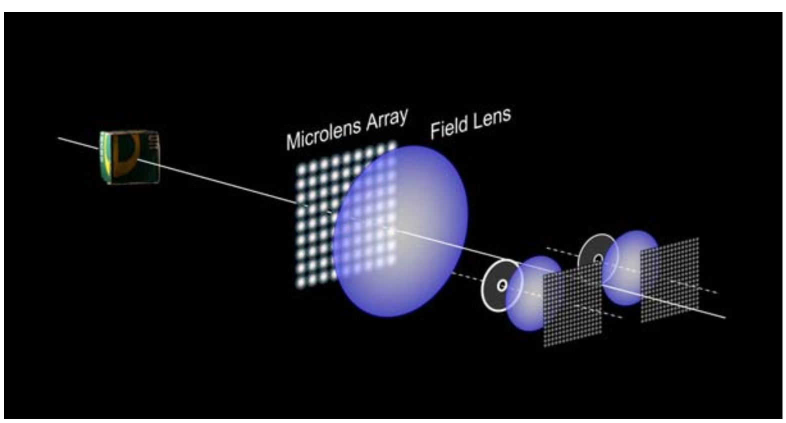


Fig. 8 Sketch of the experimental pickup with a two axes MATRES.

To illustrate the MATRES we performed a hybrid experiment in which, again, the pickup was obtained experimentally in the laboratory, but the reconstruction stage was the result of a computer processing. In Fig. 8 we show the layout of the experimental setup. For this experiment we implemented a MATRES with only two axes, so that the viewing only was, only, doubled. As the 3D scene we used a green die placed at a distance of 60 *mm* from the MLA. The MLA was composed of 51×51 square microlenses of $1.01\,mm \times 1.01$ mm in size and focal length of f=5 *mm*. The two sets of elemental images obtained with the MATRES are shown in Fig. 9. 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. 10. The improvement of the viewing angle is apparent.

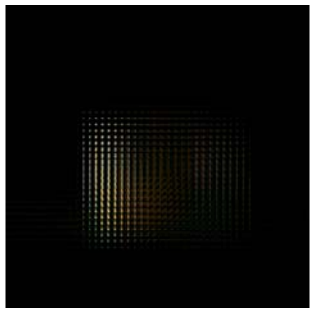
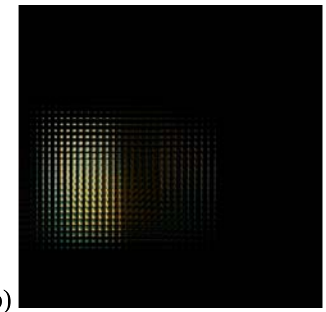
(a)  (b) 

Fig. 9 Set of 51x51 elemental images obtained with: (a) The left-hand side camera lens; (b) The right-hand side camera lens.

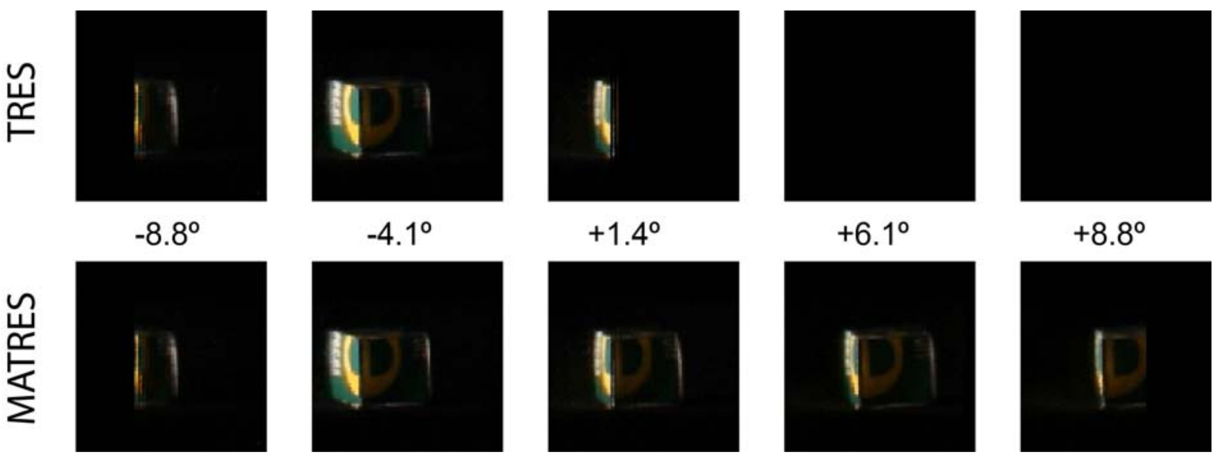


Fig. 10 Reconstructed images obtained with conventional TRES and with the MATRES.

6. CONCLUSIONS

We have performed a review of the achievements of our group in the context of InI systems. Specifically, we have show an optical technique, the TRES, for improvement of the depth of field of recorded elemental images and also for the improvement of resolution of reconstructed images. A developed version of the TRES is the MATRES, which permits by optical method the triplication of the viewing angle of InI monitors. Other achievements of our Group, not shown here, are for example the development of a simple technique for the pseudoscopic-to-orthoscopic conversion, or the invention of a very simple technique for implementation of arrays of zoom micro-lenses.

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