Optically-corrected elemental images for undistorted Integral image display

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Abstract: Conventional macro objectives are generally used as relay systems in the capture stage in Integral Imaging. This choice leads to microimage overlap and shift, which produce undesirable effects on the reconstructed three-dimensional images, such as loss in resolution and image distortions. In this paper, we propose and demonstrate a new architecture for the capture stage. Our method uses a telecentric relay system to overcome the conventional drawbacks. Experiments conducted with our system show an important improvement in the quality of displayed images.

OCIS codes: (110.6880) Three-dimensional image acquisition; (110.4190) Multiple imaging

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1. Introduction

Three-dimensional (3D) image recording and visualization have been subjects of great interest [1-4]. Among the proposed techniques, Integral Imaging (InI) stands out in providing autostereoscopic images with full parallax. Based on the principle of Integral Photography [5-6], InI has became a promising procedure to produce real-time 3D imaging [7, 8]. In the past few years important research efforts have been addressed to overcome fundamental limitations of InI, such as the limited extension of the depth of field [9-12], the enhancement of the viewing angle [13-14], the generation of orthoscopic integral images [7, 8, 15] and the improvement of the quality of displayed images [16-17]. There have been remarkable practical advances by designing 2D-3D displays [18] and multiview video architecture and rendering [19]. Another topic of interest has been the search for procedures for minimizing the overlap between microimages when capturing large 3D scenes. The insertion of opaque barriers, commonly known as optical barriers, could solve this problem. However, the technical implementation of these barriers is very complicated and has been demonstrated only in the case of bigger lenses, and in the display stage [20]. The use an array of GRIN microlenses to obtain the collection of non-overlapped microimages, as proposed by Okano and co-workers [21], is more feasible. Note however that GRIN lenses have limited performance in non-paraxial imaging, that is, when imaging with large perspective angles. The use of arrays of couplings of two [22] or three convergent lenses [23] can also contribute to reduce the overlapping problem. There exists another technique for the reduction of overlap between microimages. It is somewhat surprising that although such technique is extensively used in the pickup process, no explicit reference to its utility for overlapping reduction can be found in the bibliography. We refer to the use of a relay system. Such a system was originally intended for projecting, with the proper magnification, the microimages onto the pickup device [7]. However, as we show later, the relay system inherently produces a second beneficial effect: a strong reduction in the overlapping between microimages. Nevertheless, this way of proceeding still suffers from two highly inconvenient drawbacks. On the one hand, the microimages do not match the corresponding elemental cells, but are shifted towards the optical axis of the macro. On the other hand the microimages are not sharply separated on the recording plane, so that each microimage still overlaps with the neighboring ones. These geometrical distortions lead to undesirable effects in the display stage, like loss of resolution or image distortions. These effects have dramatic consequences on the visual quality of reconstructed 3D images.

The aim of this paper is to design a new architecture for the pickup setup, which allows the acquisition of a non-overlapped, un-shifted collection of microimages. The cornerstone of this new architecture is the telecentricity of the relay system. In Section 2 we analyze the structure of the microimage collection, and propose a new system for eliminating the microwindows shift and the overlapping effect. In Section 3 we present experimental results and compare the results obtained with the standard pick-up and with the proposed architecture.

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2. The windowed structure of the microimage set

Let us start by drawing a schematic configuration of an InI system. As shown in Fig. 1, in the pickup stage a collection of elemental images, each with different perspective of the 3D scene, is generated onto the pickup device. In the reconstruction process the recorded elemental images are displayed by a photonic device, like an LCD, placed just in front of another microlens array. Although all the elemental images are imaged by the corresponding microlenses onto the reference image plane, the 3D scene is reconstructed in the image space by the intersection of the ray bundles emanating from each of the microlenses. Note however that the schematic geometry shown in Fig. 1 cannot be used for real pickup. One problem comes from the small size of pickup devices, which would allow the capture of only elemental images with small perspective angle. To describe in comprehensive form the second problem and the technique for overcoming it, we need to define some nomenclature: A *microimage* is the 2D image of a 3D scene produced by a particular microlens. The size of any microimage is proportional to the transverse size of the 3D scene. An *elemental cell* is the region of the CCD with the same size and position as the corresponding microlens. The CCD is divided into a collection of elemental cells. When using a relay system the elemental-cells grid is properly scaled. An *elemental image* is the portion of the microimage that falls within the corresponding elemental cell.

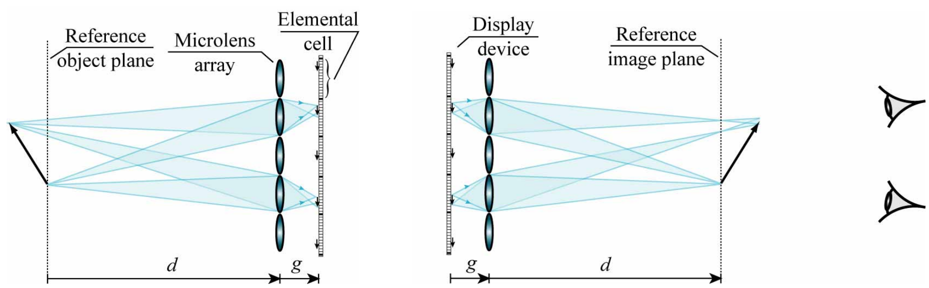

Fig. 1. Schematic configuration of pickup and display of a InI system.

The second problem comes from the fact that when capturing large scenes, the different microimages are much larger than the corresponding elemental cells, giving rise to a strong overlapping between microimages. In this case, any elemental cell receives light from many microlenses and therefore no useful information can be extracted from them.

The use of a relay system was proposed for solving the problem resulting from the difference in size between the microlens array and the pickup device [7]. But, additionally, the relay system provides a partial solution to the overlapping problem. In practical realizations of InI a macro objective is commonly used as the relay system [24]. In Fig. 2 we have schematized the macro objective by means of a converging lens, the macro lens, and an aperture stop. In this scheme we have assumed that, in general, the aperture stop is not at the back focal plane of the macro objective. We restrict, at this stage, our analysis to the field of at least one-half illumination corresponding to an arbitrary microlens. The bounding rays for such field are rays that pass through the center of the relay-system aperture stop and the edges of the microlens (see dark green ray bundles). As we see, due to the presence of the relay system, now the

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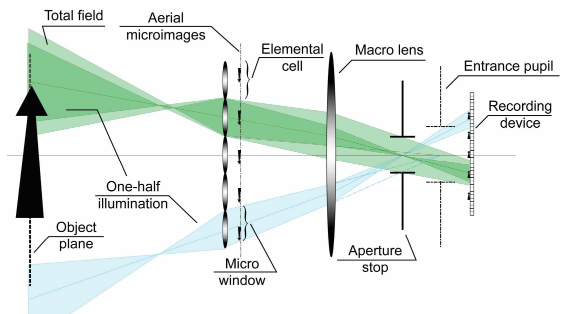

Fig. 2. Scheme of conventional pickup stage of an InI. The relay optics allows the acquisition of higher number of microimages. The micro-windows are smaller than the elemental cells, and shifted towards the optical axis of the macro.

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-window. These micro-windows 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 be the responsible for important image distortions in the reconstruction stage. Besides, the micro-windows 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 edges of the microlens and the edges of the relay-system aperture stop (see bright green ray bundles). We find an important overlapping between neighbor micro-windows. This overlapping effect will impoverish the resolution in the reconstructed 3D image.

To allow high-quality 3D reconstructions, the pickup process must be optimized. A pickup architecture that provides a collection of non-overlapped micro-windows whose size and position match the elemental-cell grid is needed. To obtain this one should realize that: (a) the center of each micro-window 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 size of each micro-window is determined by joining the center of the relay-system EP with the edges of the corresponding microlens. Therefore, to allow the micro-windows collection to match the elemental-cells grid, a relay system in which the EP is placed at infinity is needed. Such arrangement ensures that the conjugate of this EP through the different microlenses, which will be called micro-EPs, are centered just in front of the center of any microlens. In other words, the relay system must be telecentric in its object space [25] and with an aperture stop such that the corresponding micro-EPs are small enough to minimize the overlapping. However, since when the micro-EPs are too small diffraction effects appear, the proper selection of the aperture stop diameter should be the result of the trade-off between the overlapping effect and the diffraction limit.

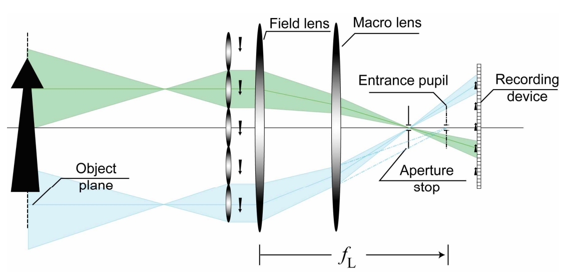

Fig. 3. Scheme of proposed pickup stage. The telecentric relay system allows the micro-windows to match the elemental-cell grid.

The proposed architecture for the pickup stage is shown in Fig. 3. The relay system is composed by a large diameter converging lens, the field lens, and a macro objective which, as in Fig. 2, is schematized by the macro 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 microimages that match the elemental-cell grid. Note that since now the micro-windows have the same size than elemental cells the elemental fields of view are wider than the ones obtained with the conventional relay. In other words, this setup permits the acquisition, by optical means, of the correct elemental-image collection.

3. Experimental results

Let us remark that 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 [26]. In Fig. 4 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. The system was adjusted so that the letter *G* was in focus. We added a double-line square surrounding each target to make the

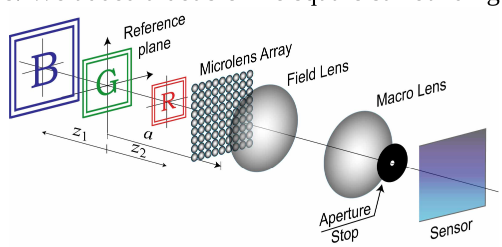

Fig. 4. Experimental setup. The axial distances are a=100 mm, z_1=-60 mm and z_2=50 mm.

focusing task easier. The size of the letters was set so that they provide micro-images with the same resolution.

The targets were illuminated with the white light proceeding from a fiber-optic bundle illuminator. A microlens array composed of 39 × 27 square microlenses of 1.01 mm × 1.01 mm in size and focal length of f=3.3 mm was used to obtain the microimages. A Canon 60 mm macro objective in combination with an achromatic field lens that is 2 inches in diameter and 200 mm in focal length, were arranged to form the telecentric relay. Thus, the distance between the field lens and the macro lens was adjusted so that the back focal plane of the field lens matched the EP of the macro objective. Specifically the distance was 118 mm. The macro f # was set to 10. The elemental images were recorded onto the color CMOS detector of a Canon EOS 350D camera, consisting of 3456 × 2304 square pixels in a 22.2 × 14.8 mm area.

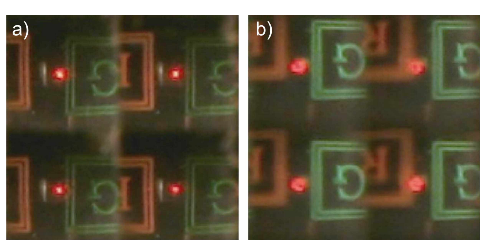

Fig. 5. Set of 2x2 microimages recorded by using: (a) the telecentric relay system; (b) the conventional relay system.

To check the ability of our setup to provide non-overlapped microimages we registered the collection of microimages with the telecentric setup, and also with the standard setup in which the field lens is not used. A subset of 2 × 2 micro-images is shown in Fig. 5. In the figure we can see the strong overlapping between microimages provided by the conventional setup. The overlapping is clearly minimized with our setup.

To check if the micro-windows matches the elemental cells, we additionally back-illuminated the targets with a collimated beam proceeding from a He-Ne laser. Since the laser beam was parallel to the optical axis of the system, every microlens focuses the incoming light onto its own axis. The collection of spots provided a labeling of the centers of the elemental cells. The microimages registered with our system and with the conventional system are shown in Fig. 6. In the figure we have prepared a movie in which we show frame by frame 32 microimages of the same row of the microimage collection. The left-hand figure corresponds to the images registered with the telecentric relay. Note that here the laser spot is always at the center of the elemental cell. So, there is no shift between the micro-windows and the elemental cells. In the right-hand movie we show the microimages recorded with the conventional relay. In this case, the micro-windows are increasingly displaced, relative to the elemental cells. Specifically micro-windows are displaced towards the optical axis of the macro, and therefore they are no longer centered at the center of the elemental cells. Note that in the conventional-relay movie the spots were slightly blurred. It was due to the fact that in such case the laser beam collimation was slightly worse.

To illustrate our method we have simulated the reconstruction stage. In our calculations we assumed that the display is done with the same microlens array as in the pickup. Since the micro-windows obtained with the conventional relay were smaller than the elemental cells, they were magnified so that they matched the elemental cells. As a result of such magnification the resulting microimages had bigger scale than the ones obtained with the telecentric relay. To allow a virtual, orthoscopic reconstruction we followed the method proposed by Okano [7], and therefore each microimage is individually inverted by a 180º rotation. As consequence of the scaling and the shift suffered by the microimages captured with the standard relay, the reconstructed images were smaller that the corresponding objects, and therefore smaller than the images reconstructed from the microimages recorded with the telecentric relay. In Fig. 7 we show the calculated reconstructions. In our calculations we assumed an observer placed is at a distance D=400 mm from the microlens array and that displaces laterally from x=-28 mm to x=+28 mm. The position x=0 corresponds to the case in which the observer's eye is centered at the optical axis of the central microlens. From the movies 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.

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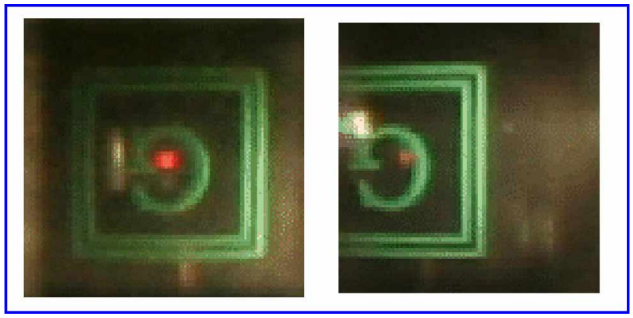

Fig. 6. Sequence of 32 microimages obtained by using the telecentric relay (left movie) and the conventional relay (right movie). (Video file of 0.79 Mb)

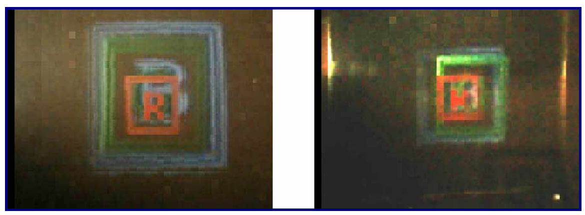

Fig. 7. Reconstructed images calculated from the microimages captured with the telecentric pickup (left movie) and with the conventional pickup (right movie). (Video file of 0.6 Mb).

4. Conclusion

We have presented a purely-optical technique for acquisition of the collection of non-overlapped, un-shifted elemental images of large 3D scenes. The technique is simply based on the use of a relay system that is arranged in a telecentric manner. We have performed a hybrid experiment that shows that our proposed setup provides reconstructed 3D scenes with much better resolution, without distortions in scale, and even with better depth of field.

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