Orthoscopic, long-focal-depth 3D Integral Imaging

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ABSTRACT

Integral imaging systems are imaging devices that provide 3D images of 3D objects. When integral imaging systems work in their standard configuration the provided reconstructed images are pseudoscopic; that is, are reversed in depth. In this paper we present, a technique for formation of real, undistorted, orthoscopic integral images by direct pickup. The technique is based on the use of a proper relay system and a global mapping of pixels of the elemental-images set. Simulated imaging experiments are presented to support our proposal.

Key words: Integral imaging, 3D imaging display, digital 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 four years it can be recognized that we have already made some interesting contributions, which help to deal satisfactorily with some of the main challenges of 3D imaging recording/display system. This paper is devoted to review these achievements. Specifically, we show an optical technique for improvement of the depth of field in the pickup stage, which allows the recording of sharp elemental images for a long range of axial positions. Besides, we present a technique that minimizes the overlap, also known as interference, between elemental images by means of an adequate arrangement of the pickup relay system. Finally we present a image processing technique that globally rearrange the pixels of the integral-image collection, so that a real orthoscopic image reconstruction is possible.

2. PRINCIPLES OF INTEGRAL IMAGING

In Lipmann scheme, photography of a self-luminous 3D scene is taken through a pinhole array (see Fig.1). 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 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.

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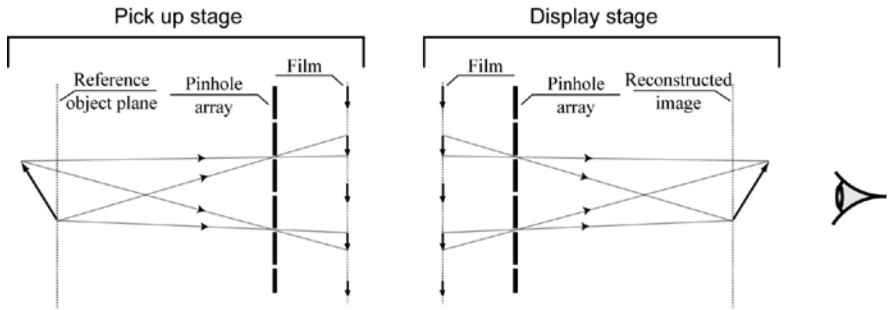

Figure 1.- Scheme of the integral photography method proposed by Lipmann.

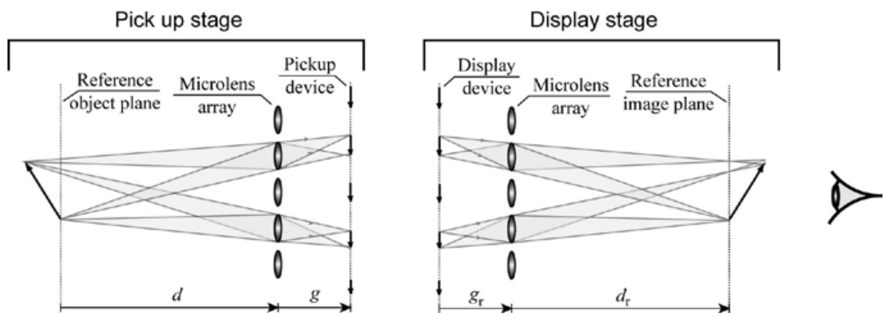

Figure 2.- Scheme of an integral imaging system

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 matricial 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 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.

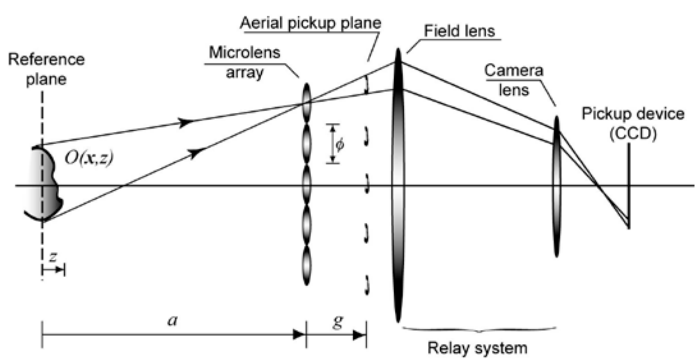

Figure 3. Scheme, not to scale, of the capture setup of a 3D InI system. Object points out of reference plane produce blurred images in the CCD. In the relay system the field lens collects the rays from the outer microlenses; the camera lens projects the images onto the CCD.

Note however that this schematic geometry cannot be used for real pickup. The problem comes from the small size of pickup devices, which would allow the capture of only elemental images with small perspective angle. It is then necessary the use of a relay system, which is intended for projecting, with the proper magnification, the microimages onto the pickup device, allowing then the capture of higher number of undistorted microimages, see Fig. 3.

3. IMPROVEMENT OF DEPTH OF FIELD IN THE PICKUP STAGE

One of the challenges that InI is facing is the limited depth of field. In a typical scene objects exist at different depth positions. Since only a single object plane is used to capture the images, it is not possible for all objects to be in focus. Then blurred images of out-of-focus objects are obtained. Although the depth of field of integral imaging systems is influenced by many parameters (related with both the capture and the display systems), it is apparent that to display a clear integral image of an axially elongated 3D object it is essential to capture sharp 2D elemental images of it. For this reason, the bottleneck of the depth of field in integral imaging is the limited depth of field of the microlens array used in the pickup stage. One could overcome this problem by reducing the numerical aperture (NA) of the lenses. However, such a reduction would produce, as a collateral effect, an important worsening of lateral resolution of capture stage, and therefore of spatial resolution of the overall integral imaging system. To illustrate the influence of diffraction onto the limitation in depth of field in the pick stage we have simulated the pickup experiment shown in Fig. 4.

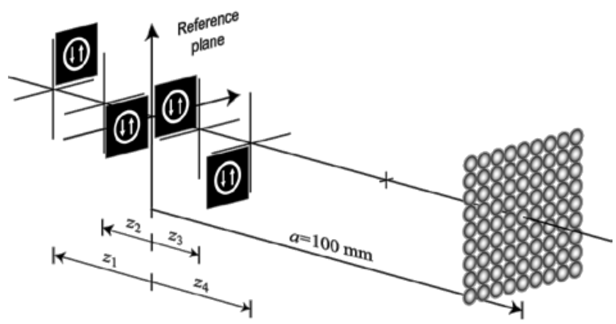

Figure 4. Simulated pickup experiment to show the limitation in DOF of an InI system.

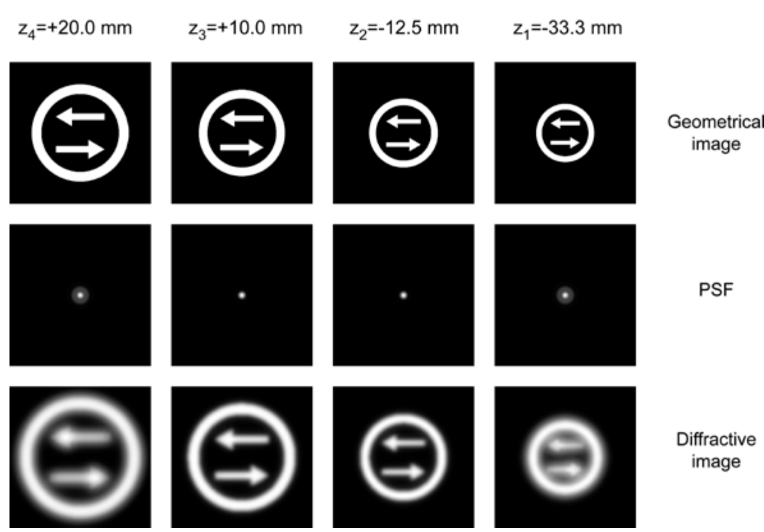

Figure 5. Diffractive image of out-of-focus scenes.

In this simulation we inserted a test object in four different axial positions. Two of them with small defocus. The other two with high defocus. Note that we selected axial positions with the same amount, but different sign, of defocus. Then the corresponding intensity PSFs have the same form and size, as seen in Fig. 5, where we see that the PSFs of positions z_1 and z_4, and the ones of positions z_2 and z_3, are equal. However, to form the image the PSFs must be convolved with differently scaled versions of the object. Therefore, same amount of defocus does not provide the same blurring, so that closer objects are less affected by defocus. Any way, we see that due to diffraction, part of the 3D scene far from the reference plane produce elemental images that are not sharply recorded, an therefore that cannot be sharply reconstructed.

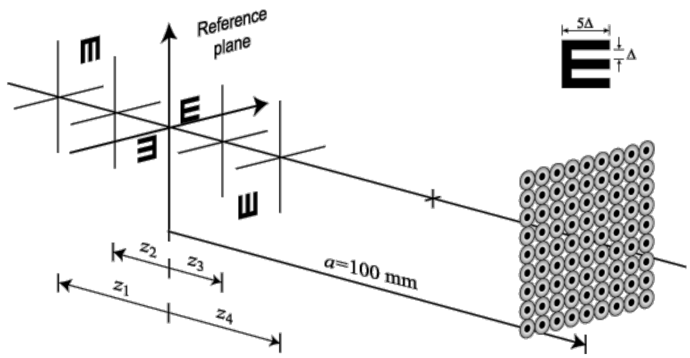

Figure 6. Simulated pickup experiment in which the annular aperture is inserted as entrance pupil of the microlenses.

Our proposal to overcome this problem is based on the use of binary amplitude modulation technique. As well known, an imaging system whose aperture stop is apodized with an annular aperture, produce a diffractive spot that, when compared with the one produced by the usual circular aperture, is narrower in the lateral direction and much larger in the axial direction. This allows the production of images with higher depth of field and no deterioration of lateral resolution. The only real problem of this technique, when applied to InI systems, is how to insert the grid of annular apertures in front of the array of microlenses. We have found however a very simple, cheap optical technique to resolve such problem. Our solution consists on the use of a proper relay system that allows the projection of a grid of microimages of a unique annular hard aperture, onto the front focal plane of any of the microlenses (see Fig. 6).

As we can see in Fig. 7, the use of the annular apertures allows the significant improvement of the depth of field of pickup system, allowing then the capture of sharp images for a large range of axial positions.

(a) (b)

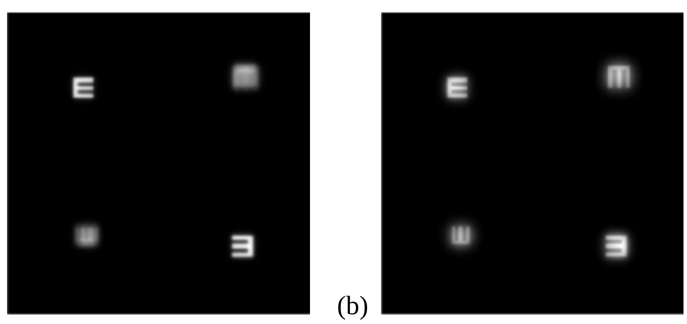

Figure 7. .Elemental images obtained with: (a) The array of microlenses with circular aperture; (b) The array of microlenses with annular aperture.

4. PSEUDOSCOPIC TO ORTHOSCOPIC CONVERSION

Let us consider the standard configuration of an InI system, as shown in Fig. 2. In the pickup stage the system is adjusted so that a representative plane of the object neighborhood, referred here as the reference object plane, and the CCD plane are conjugated through the microlenses. Distances d and g are, then, related through the lens law, $1/d+1/g=1/f$, f being the lenslets focal length. Then, a collection of elemental 2D images, each with a different perspective of the 3D object, are generated onto the pickup device. In the reconstruction process the recorded elemental images are displayed by an optical device (like a LCD) in front of the other microlens array. The LCD and the microlens array are adjusted so that the gap, g_r, is the same as the pickup gap, g. As shown in the figure this architecture permits the reconstruction of a real but pseudoscopic image at a distance $d_r = d$. The first attempt to overcome this problem was done by Ives [16] who, in the context of IP, proposed to record a second set of elemental images, by using the reconstructed image as the object. As we show in Fig. 8, when the second set of elemental images are used in a second reconstruction stage, a real, undistorted, orthoscopic 3D image is reconstructed. This proposal does not constitute an effective solution for the 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 [1].

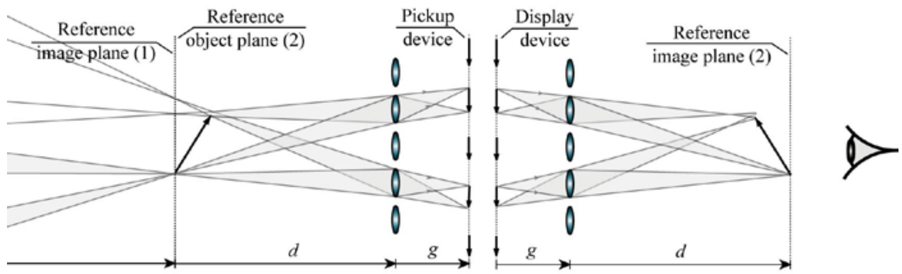

Fig. 8 PO conversion method proposed by Ives. The reconstructed image is used as the object for a second pickup. The second display provides the observer with a real, undistorted orthoscopic image.

A different approach was suggested by Davies et al. [17], who proposed the use of an auto-collimating transmission screen placed between the object and the InI microlenses. The auto-collimating screen has the property of bending any incoming ray so that the incident angle equals the emerging angle, producing then a depth-reversed, undistorted image of the 3D object. When this image is used as the object for the pickup stage of an InI system, the reconstruction system provides a virtual, undistorted orthoscopic 3D image. However, although this scheme does not need for two recording stages, it still suffers from some drawbacks. On the one hand, the use of the auto-collimation screen enhances the detrimental effects of diffraction onto resolution. Besides, the reconstructed image is virtual. However, the formation of a real image of the object is often preferable because such 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 [18]. A very smart and simple scheme was suggested by Okano and co-workers [4]. They proposed to capture the elemental images with the standard pickup architecture. Then, each elemental image is rotated by 180º 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. When these rotated elemental images are displayed at a distance $g_v=g-2f^2/(d-f)$ [19], a virtual, undistorted orthoscopic image is obtained at a distance $d_v=d-2f$ from the lenslets array. Note that to obtain a reconstructed virtual image, a double condition is necessary. On the one hand, any microlens must produce in the reference plane a virtual image of its corresponding elemental image. On the other hand, the set of ray-cones corresponding to the same point of the object must intersect in the same virtual point of the reconstructed image, as shown in the figure. Although in this scheme there is no degradation of the image due to the introduction of additional elements or stages, it still has the drawback that the reconstructed image is virtual. Some other methods have been proposed for the PO conversion either in transmission architecture [20], or by using micro-convex mirrors [21].

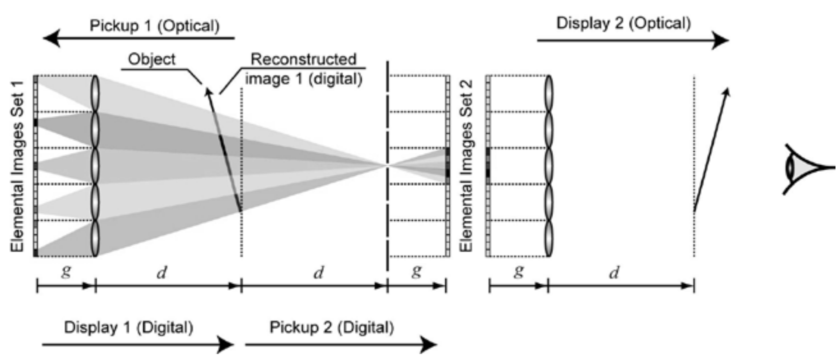

Fig. 9 Scheme of the PO digital conversion method.

Let us concentrate, to finish, in the method suggested by Jang and Javidi [22]. Their scheme is similar to the one proposed by Davies et al., but the auto-collimating device is substituted by a converging lens. Then as shown in Fig. 5, in the pickup the elemental images of a depth reversed version of the object are recorded at $g_v=df/(d+f)$. In the display the elemental images are rotated by 180º and the gap is shifted to $g_r = d\,f/(d-f)$. Then, a real, orthoscopic image of the 3D object is reconstructed. However, due to the non-constant lateral magnification of the converging lens, the reconstructed image appears clearly distorted.

Among the techniques analyzed above, the only one that satisfies the requirement of providing real, orthoscopic 3D images is the one proposed by Ives. However, the practical application of this technique is not very advantageous because the two-step recording/displaying technique produces a strong degradation in the image. What we suggest here is to make use of Ives PO concept but, in order to avoid the disadvantages of the two-step process, we propose to perform the intermediate stage (Display 1 + Pickup 2) by digital procedure. On the basis of the scheme shown in Fig. 9, we will explain the PO digital procedure for the 1D case. The extension to the 2D case is straightforward. Since we assume that the optically-acquired set of elemental images (Set 1) have a pixilated structure, it is clear that the conversion to the second set of elemental images (Set 2) will simply consist in a pixel mapping. Then, to avoid typical aliasing problems in the pixels mapping, it is necessary to assume that the following relations are satisfied: $N = mM$ and $M = 2d/g$, where N stands for the number of pixels per elemental cell, M is the number of elemental images, and m is a positive integer number. 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.

To illustrate our approach we have simulated the experiment shown in Fig. 10. In Fig. 11 we show both, the original and the mapped collection of elemental images. Finally in Fig. 12 we simulated the observation by an observer that looks towards the central microlens, and displaces the eye horizontally from x=-25 mm to x=-25 mm.

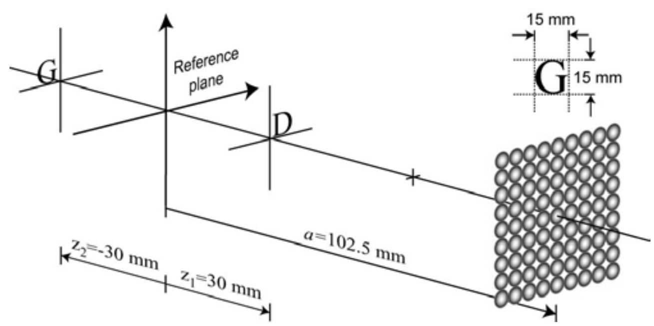

Fig. 10. Scheme, not to scale, of the pickup numerical experiment. The CCD is adjusted so that the reference object plane is at 102.5 mm. The letters are separated by 60 mm in depth.

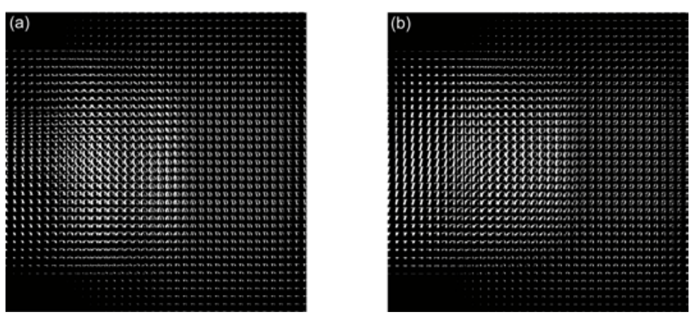

Fig. 11 (a) Collection of 39×39 elemental images obtained with the setup of previous figure; (b) Elemental images obtained after applying the smart pixel mapping.

Fig. 12 (a) Real, pseudoscopic image calculated from the elemental images in Fig. 11(a); (b) Real orthoscopic image calculated from the elemental images in Fig. 11(b). In both reconstructions we assume that the observer is placed at 500 mm from the microlenses, and he/she laterally displaces the eye from left to right The eye displacement is from x=-25mm to x=+25 mm.

5. CORRECTION OF MICROIMAGES OVERLAP AND SHIFT

As shown in Fig. 2, in the pickup stage a collection of elemental images, each with different perspective of the 3D scene, is generated onto the pickup device. Note however that this schematic geometry cannot be used for real pickup. The 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.

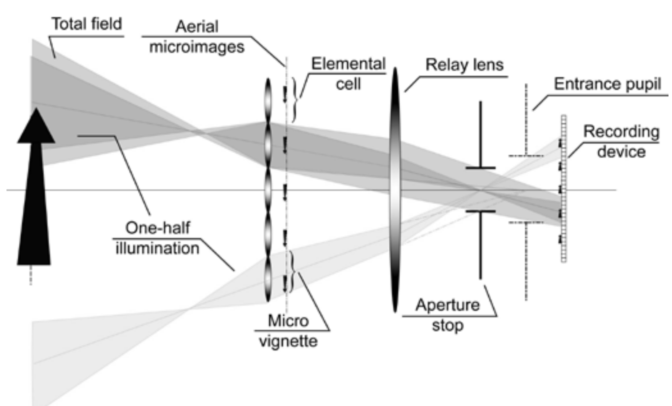

Fig. 13 Scheme of conventional pickup stage of an InI. The relay optics allows the acquisition of higher number of microimages. The microimages size and position is determined by the vignetting effect.

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. 13 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. 13). We find now an important overlapping between neighbor micro-vignettes. This overlapping effect will impoverish the resolution in the reconstructed 3D image.

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 [23] and with an aperture stop such that the corresponding micro-EPs are small enough to minimize the overlapping. However, one must take into account that when the micro-EPs are too small diffraction effects do appear, which impoverishes 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.

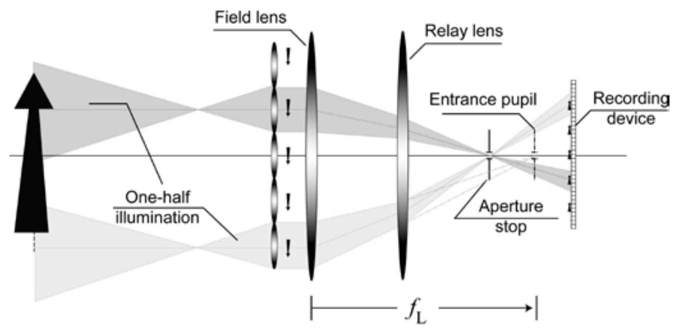

Fig. 14 Scheme of proposed pickup stage. The telecentric relay system allows the micro-vignettes to match the elemental-cells grid.

On the basis of the above reasoning, we propose a new architecture for the pickup stage. Our proposal is schematized in Fig. 14. The relay system is composed of a high-diameter converging lens, the field lens, and a macro objective, which as in Fig. 2 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 microimages that match the elemental-cell grid. In other words, this setup permits the acquisition, by optical means, of the correct elemental-image collection.

6. CONCLUSIONS

We have performed a review of the achievements of our group in the context of InI systems. Specifically, we show an optical technique for improvement of the depth of field in the pickup stage, which allows the recording of sharp elemental images for a long range of axial positions. Besides, we present a technique that minimizes the overlap, also known as interference, between elemental images by means of an adequate arrangement of the pickup relay system. Finally we present a image processing technique that globally rearrange the pixels of the integral-image collection, so that a real orthoscopic image reconstruction is possible.

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