Optical barriers in integral imaging monitors through micro-Köhler illumination

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ABSTRACT

Usual problem in 3D integral-imaging monitors is flipping that happens when the microimages are seen from neighbor microlenses. This effect appears when, at high viewing angles, the light rays emitted by any elemental image are not passing through the corresponding microlens. A usual solution of this problem is to insert and a set of physical barriers to avoid this crosstalk. In this contribution we present a pure optical alternative of physical barriers. Our arrangement is based on Köhler illumination concept, and avoids that the rays emitted by one microimage to impinge the neighbor microlens. The proposed system does not use additional lenses to project the elemental images, so no optical aberrations are introduced.

Keywords: 3D display, integral imaging, image flipping, Köhler illumination.

1. INTRODUCTION

The generation and visualization of three-dimensional (3D) images has been object of study and development for more than a century and half, and nowadays still is a challenge in the development of modern 3D displays. In the past few years, a technique based in the integral photography proposed by Lippmann in 1908 [1], the integral imaging (InI) technique, has attracted great the interest due to its capacity for displaying autostereoscopic 3D images with full color and quasi-continuous motion parallax at any direction of viewing. A fundamental aspect in the rebirth of the integral imaging is the improvement of the key technologies needed to increase the quality of the 3D images displayed, such as dense microlens arrays and high-resolution digital sensors and displays. Furthermore, computational techniques offer new applications beyond the physical projection of the 3D images, as volumetric reconstruction, depth mapping, object recognition or focusing at different planes after the image has been taken [2].

The basis of the autostereoscopic 3D effect observed with an InI based display is the simultaneous projection of multiple views of the scene with an array of microlenses. The first step is to record the multiples views. To do so, an array of microlenses is placed in front of a single digital sensor, so that it is recorded an array of microimages, each with a different perspective of the scene. The 3D information is coded in the disparity of equivalent points between the views, as in typical multi-cameras systems. In the projection stage, the views are displayed in a monitor and projected through an array of microlenses placed on the display panel. Each microlens projects its corresponding view onto an intermediate space between the display and the observer, so the structure of the light of the scene separated in the recording stage is reconstructed by the superposition of the views in this intermediate plane, following the reverse path.

A major drawback in InI based projectors is the narrow viewing angle in which the 3D image can be observed with continuous parallax. This limitation starts in the capture stage and is connected with small field of view of the microimages [3]. Because in the capture stage is used the same sensor to record at the same time all the microimages, it

Three-Dimensional Imaging, Visualization, and Display 2015, edited by Bahram Javidi, Jung-Young Son, Proc. of SPIE Vol. 9495, 94950L · © 2015 SPIE CCC code: 0277-786X/15/\$18 · doi: 10.1117/12.2177692 is necessary to limit individual regions in the sensor, typically equal to the size of the microlens, where each microimage can be recorded separately from the others; otherwise, the microimages of large scenes will overlap with the neighbor ones, and the three-dimensional information will be confused within the overlapped region. A solution to solve this issue is to use a telecentric relay system behind the microlens in order to project the microimages parallel each other [4]-[5].

In the projection stage, the microimages are projected through the microlenses, so now it is necessary to limit the FOV "seen" by each microlens to the size of the corresponding microimage. Otherwise the microlens will project also the neighbor microimage. The crosstalk of microimages causes image flipping when the observer sees the InI display from an angular field of view bigger than the microlens viewing angle. However, the crosstalk issue can be used as an advantage to enhance the angular FOV of the integral imaging display combining time multiplexing projection and eye tracker techniques [6]. Advances in projection techniques make it possible to solve the problem of implementing the barriers [4], [5], [7], [8], but these systems are complex and very sensitive to misalignments and aberrations since the microimages are projected through a set of lenses.

In order to solve the crosstalk problem in the projection stage, we present a system based in Köhler illumination, which imposes the projection angle of individual microimages to match the exit angle of the corresponding microlens. Since the arrange of additional lenses is used only to illuminate the panel, the standard configuration (display panel and microlens array), is respected and no additional aberrations are added. In the following, we first explain the basic principles of integral imaging in Section 2 and Köhler illumination in Section 3. In Section 4 we explain the proposed method, and finally, in Section 5, we demonstrate experimentally the performance of the Köhler based system.

2. PRINCIPLES OF INTEGRAL IMAGING

Principles of integral imaging

In the simplest setup of an integral imaging system, as shown schematized in Fig. 1(a), the image of the scene is recorded as an array of microimages (called integral image) when incoming rays of light are focused onto the sensor through an array of microlenses (MLA). Normally, the size of the MLA is greater than the sensor, so it is common to use an optical relay behind the MLA to focus the aerial integral image with the appropriate scale. In other setups, the array is close to the sensor and both have the same size, but the scene is far from them and the optical relay is used to focus the scene in planes next to the microlens array [9]. However, using an optical relay does not alter the fundamentals of the 3D capture, which relies in the fact that in the integral image the 3D information is coded in the different perspectives of the scene taken with the corresponding microlens.

A major drawback in the recording stage is the overlapping between neighbor microimages. This gives rise to the loss of resolution in the reconstructed image as no useful information can be extracted from the overlapped region. To avoid overlapping it is necessary to limit a region in the sensor, usually named elemental cell, in which every microimage (also called elemental image) can be recorded separately from the neighbor. A conventional solution is the use of opaque physical barriers between the microlenses, but others employ the optical relay to limit the field of view (FOV) of the microlenses to the appropriate size [4]-[5], [10], [11]. Typically the FOV is matched to the pitch of the microlenses, in such a way that the microimages are joined together. In this case, the maximum angular field of view recorded by a microlens is given by

$$\Omega_{\max} = 2 \arctan\left(\frac{p_s}{2g_s}\right),\tag{1}$$

where p_S is the MLA pitch and g_S is the gap from the MLA to the sensor. When the 3D display is aimed, the maximum angular field of view of the elemental images determines the maximum range of parallax of the 3D display, since it establishes the maximum disparity with which a source point *S* can be recorded within the elemental images.

In the display stage, the integral image is sized according to the scale of the projection system and is projected with an array of microlenses placed just behind. Now, each microlens focuses the corresponding elemental image on the reference image plane of the microlenses, and the rays follow the reverse path as that in the recording stage. The 3D image is reconstructed by the intersection of rays coming from equivalent points, S', within each elemental image. Since each ray converges from the microlenses to the intersection point with a different angular position, an observer placed in front of the 3D display will see the reconstructed point, S_R , at the same angular positions, resulting in a three-

dimensional perception with true parallax within this angular field of view. This field of view has been fixed during the recording stage and determines the visualization angle of the integral imaging based display. When the observer sees the 3D monitor from an angle beyond the visualization angle, appears a new pseudo-image due to the crosstalk of elemental images when they are viewed from the neighbor microlenses instead of the corresponding one. To avoid the pseudo-images, it is necessary the use of barriers between microlenses that limit the FOV of each microlens to the size of the corresponding elemental image, thus preventing microlenses from collecting rays that emanate from the adjacent elemental images.



Figure 1. (a) Scheme of an integral imaging system for: (a) capturing, (b) projection and visualization.

3. KÖHLER ILLUMINATION

Köhler illumination is the most used method in optical microscopy. In contrast to critical illumination, where the image source of light is focused in the same plane as the specimen, thus following the same path as the image of the sample, in Köhler illumination the source of light is completely unfocused in the plane at which the observer focuses with the microscope objective. This entails that the observer will see a focused image of the sample without perceive the structure of the source of light.

The standard setup of a Köhler system for transmitted-light microscopy has key features that are shown in Fig. 2(a). A collector lens, L_F , facing the source of light generates an intermediate image of the source into the plane of an iris diaphragm, S_A , which lies just at the front focal plane of a condenser lens, L_C . In this configuration, the rays arising from the same image point of the source in the plane of S_A , are projected parallel towards the specimen plane when they pass through the collector lens, providing the uniform illumination. The diaphragm S_A controls the numerical aperture of the microscope and hence the amount of light on the objet plane and the angle of the rays passing through the specimen. Finally, an additional iris diaphragm, D_F , placed just behind the collector lens is focused by the condenser lens onto the specimen plane, so it acts as field stop limiting the field illuminated over the sample. Note that with this setup, each point in the source fills the sample at the specimen plane, whilst each point on the specimen plane is illuminated with all the extent of the source admitted by S_A .

The Köhler setup can be adapted in many different ways to suit the requirements of a wide range of illumination problems; for example, in mask lithography or in slide projection. In the case of slide projection, a setup as we schematized in Fig. 2(b) is generally used. In this setup, the slide is uniformly illuminated by the source, which is focused into the projection lens by the condenser lens. The illumination field and the illumination angle are fixed by the illumination aperture in the front side of the condenser. We have adapted this last system in order to generate the optical barriers for integral imaging display avoiding the flipping effect.



Figure 2. (a) Köhler illumination paths in transmitted-light microscopy and (b) in slide projection.

4. OPTICAL BARRIERS WITH KÖHLER ILLUMINATION

In order to implement in an integral imaging display optical barriers that limit the angle of visualization avoiding the flipping effect, a system that limits the extent of the cone of rays emitted by the any individual point in each microimage to the aperture of the corresponding microlens is needed. For this purpose a Köhler illumination based projector, as we schematized in Fig. 3, can be used.

In the micro-Köler system depicted in Fig. 3, a field lens, L_F , and a microlens array, MLA1, facing the field lens form a condenser system. As can be seen in this figure, light coming from a source of light is collected by the field lens placed just at its front focal length, f_{LF} , from the source of light. Since the source of light is at the front focal plane, the field lens turns the divergent rays arising from an individual point in the source into parallel rays. These rays arrive to the MLA1, which images the source at the back focal plane of the corresponding microlens, at a distance f_{MLI} . With this setup, the field lens and the extent of the light source impose to the rays emerging from the back side of each microlens in the MLA1 the inclination, Ω_{EI} . It turns out easy from Fig. 3, and applying basic trigonometry, to deduce that the angle, Ω_{EI} , of the rays at the exit of each microlens in the MLA1 is given by

$$\Omega_{EI} = 2 \arctan\left(\frac{d}{2f_{F_{MII}}}\right),\tag{2}$$

where d is the size of the microimages of the source in the plane of the MLA2. Since the direction of the rays passing through the EIs determine the angle of view at which they can be observed, each elemental image can only be viewed through the corresponding microlens in a second microlens array, MLA2, under the angle of view defined by Ω_{EI} . Therefore, to avoid the flipping effect at the maximum angle of visualization, the target is to match this angle to the angular FOV defined by the size of the elemental images. From Eq. 1 is straightforward that this can be done by matching the size of the image source to the pitch, p, of the MLA2, resulting

$$\Omega_{E\,\text{Imax}} = 2\arctan\left(\frac{p}{2f_{F_{ML1}}}\right) \tag{3}$$

(4)

Therefore, to achive this maximum angle, the size of the source must to accomplish



Figure 3. Scheme of the micro-Köler projection system.

With the setup explained, the micro-Köhler projector can limit the extension of angular FOV of the 3D integral imaging display to that defined by the by size of the elemental images and the relative position of the corresponding microlens used for illuminating by adjusting the extent of the source of light.

5. MICRO-KÖHLER EXPERIMENTAL RESULTS

To illustrate the flipping effect we have performed an experiment where we project an integral image captured synthetically by computer. The 3D scene and the pickup stage were built up in 3DS MAX software. The scene consisted of two identical cones at d5fferent depth from the plane of the micro-lens array, with the condition that the closest fit the FOV of the micro-lens centered at the optical axis. The MLA was simulated with an array of 50 x 50 cameras, each one with a FOV of 17.23 degrees and 33 mm of focal length. The pitch between cameras was 10 mm. The elemental image captured through the corresponding camera was rendered simulating a square sensor of 10 mm x 10 mm and 35 x 35 pixels per image. In order to experimentally observe the 3D scene the composed integral image was printed on a transparency for overhead projectors, with a resolution of 600 dpi but reducing a tenth the original size of the integral image. The integral image was placed at the back focal plane of an array of ML for the projection. The diameter and the focal length of the MLs to project the InIm was chosen according to the new scale of the elemental images: 3.3 mm of focal length and 1 mm of pitch. Because the scale factor is the same for all the parameters, the 3D scene is projected without distortions. To project the image we use a white light bulb lamp illuminating from the back side of the transparency. As an observer we use a Canon EOS 500D camera placed at a distance D=55 mm from the ML array that displaces 50 equidistant steps both horizontally and vertically. Fig. 4(H) and Fig. 4(V) show respectively six views corresponding to the observer displaced 24 horizontally from left to right and from top to bottom. In both series can be seen how from around a displacement corresponding to the maximum viewing angle, - 8 and 8 degrees, the cones begin to disappear whilst a new image of them starts to appear. When the observer moves beyond the maximum viewing angle, -12 and 12 degrees, the image of the cones disappears completely and the only image observed is the pseudoimage.



Figure 4. Flipping effect: H row corresponds to a horizontal displacement form left to right; V row corresponds to a vertical displacement from top to bottom.

To demonstrate the implementation of optical barriers from micro-Köholer setup explained, we have performed an experiment where a white light beam from a fiber source (FOI) is collected by a lens and projected through a semitransparent white diffuser film, D, which acts as a source of light. At the back side of the diffuser the extension of the source is limited by variable aperture diaphragm, VAS. Behind the diffuser and diaphragm, there is collector lens, CL, with 62 mm of diameter displaced from the VAS its focal distance, 95 mm. The CL collects the bundle of rays coming from one point at the extension of the diffuser surface limited by the diaphragm and projects the rays towards a the first microlens array, MLA1, in order to illuminate the integral image, II, which is placed attached to the back side of the MLA1. This MLA1 has the same focal length and pitch as that used in the experiment with image flipping. After the integral image, a second microlens array, MLA2, at the back focal plane of the MLA1 is used to project the integral image for 3D visualization. This MLA2 has the same features as the microlens array used for illumination. Once all the elements have been placed in the correct way, the diffuser aperture is adjusted in order to match the size of the micro-sources in the plane of the MLA2 with the size of the microlenses. In Fig. 5 we show the results obtained when the 3D image projected is observed from different points of view. In contrast to horizontal and vertical views shown in Fig. 4, views shown in Fig. 5 at the limit of the viewing angle, -8 and +8 degrees, start to darken by the effect of the optical barriers, being totally dark beyond these angles, at -12 and +12 degrees.



Figure 5. Effect of the optical barriers achieved by the micro-Köler illumination system.

6. CONCLUSIONS

We have presented a pure optical technique to implement optical barriers that avoids crosstalk of images in InI display systems. The system employs Köhler illumination to uniformly illuminate the elemental images in an integral image as a way of micro-Köhler sources. Under this configuration is possible to limit the FOV of the 3D display to that defined by the extension of the EI simply by limiting the size of the source illuminating the EI. Additional advantage is that micro-Köhler illumination enhances the contrast of the EI. We have performed an experiment that illustrates the

difference between using our micro-Köhler system and a system without barriers, demonstrating that any image beyond the FOV of the 3D display is viewed when our system is used.

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