Computation and Display of 3D Movie From a Single Integral Photography

Adrian Dorado, Manuel Martinez-Corral, Genaro Saavedra, and Seokmin Hong

***Abstract*—Integral photography is an auto-stereoscopic technique that allows, among other interesting applications, the display of 3D images with full parallax and avoids the painful effects of the accommodation-convergence conflict. Currently, one of the main drawbacks of this technology is the need of a huge amount of data, which have to be stored and transmitted. This is due to the fact that behind every visual resolution unit, i.e. behind any microlens of an integral-photography monitor, between 100 and 300 pixels should appear. In this paper, we make use of an updated version of our algorithm, SPOC 2.0, to alleviate this situation. We propose the application of SPOC 2.0 for the calculation of complete 3D traveling sequences from a single integral photograph. Specifically, our method permits to generate a sequence of 3D images that simulate the travelling 3D frames captured by a non-static cameraman. In the traveling sequence, we can fix at will, for every frame, the size and position of the field of view, and the parts of the scene that are displayed in front or behind the monitor. Our research is illustrated with experiments in which we generate and display a full traveling sequence.**

***Index Terms*—Three-dimensional (3D) image processing, multiple imaging, 3D image acquisition, displays.**

I. Introduction

CONVENTIONAL photographic cameras cannot record the angular information of rays emitted by a 3D scene. In order to record the angular information and, therefore, to display 3D images, it is necessary to resort to 3D techniques like holography, in the coherent case, or like integral photography (IP), in the incoherent case. If we focus our attention in the incoherent technique, we can start by stating that Lippmann proposed the IP in 1908 [1]. The basic idea is to record a set of different horizontal and vertical perspectives, commonly named as elemental images (EIs), of a 3D scene and use them later to display the 3D scene. The 2D image obtained after arranging the collection of EIs in a rectangular grid, will be named here as the integral photograph. By placing a microlens array (MLA) in front of the integral photograph, a binocular observer situated in front of the MLA can see the 3D reconstructed scene with quasi-continuous perspective and with full (horizontal and vertical) parallax. The main advantage of IP is that the 3D reconstructed scene can be seen without any special glasses, because of the integration of the light coming from the EIs.

During the last decades, new techniques have been proposed from the original Lippmanns method. Some of them stand out as the plenoptic camera, which permits to record and retrieve the 3D information with just one shot [2]–[4]. Particularly, some new applications and methods have been developed in the past few years like analyzing the stress state of transparent occluded materials [5], alternative process to project 3D information [6], [7] and to computationally capture a virtual 3D scene using a synthetic lens array [8]. Moreover, Lippmann's idea has been also implemented in the field of microscopy [9]. Additionally, there have been some promising attempts to produce commercial devices as a handheld plenoptic camera [10], a multi-focus plenoptic camera [11], and, although still in its early stages, an IP television [12]. Because IP can be used in many applications, there is a great interest to further improve this method and to overcome some of its drawbacks. In order to increase the angle of vision in IP, Miura *et al.* tilted the MLA to obtain horizontally enlarged EIs [13] and Chen *et al.* used an adaptive liquid crystal prism array to electronically refract the EIs [14]. Tilting the MLA was also the solution proposed by Kim *et al.* [15] aiming to reduce the color moir pattern. On the other hand, an improvement of the lateral resolution in IP can be obtained by a double shot mechanism [16], [17]. Also, it is possible to improve the quality of the reconstructed images by extending the depth of field of an IP system using deconvolution [18] or a bifocal liquid crystal lens [19]. Another approaches are moving the reconstructed object within the depth of field as in [20] and [21], or refocusing the elemental images as in [22]. Studies to better understand this technique have been performed. In particular, the resolution of IP was thoroughly analyzed in [23].

In this paper, we report a procedure that is fully devoted to the production of 3D displayable content. Specifically we report a computational technique for the generation of complete 3D travelling sequences from a single integral photograph. The

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This paper contains supplementary multimedia material provided by the author, available online at http://ieeexplore.ieee.org. The supplementary file contains four videos (MEDIA1.avi; MEDIA2.avi; MEDIA3.avi; and MEDIA4.avi). MEDIA1 is a video traveling obtained from one integral image. The video shows a whole movie in which it is synthesized the travelling movement of a cameraman through the 3D scene. MEDIA2 is a video recording the 3D display of the video in MEDIA1 when projected by the integral photography monitor. In the video it shows a whole 3D traveling sequence with full parallax. MEDIA3 is an integral photography video of a 3D scene in which the position of a doll changes. Each frame of the video is obtained from a different integral photography. The field of view and the reference plane in each frame changes in order to follow the trajectory of the doll. MEDIA4 is a video recording the 3D display of the video in MEDIA3 when projected by the integral photography monitor. The total size of the file is 85 MB.

Color versions of one or more of the figures are available online at http://ieeexplore.ieee.org.

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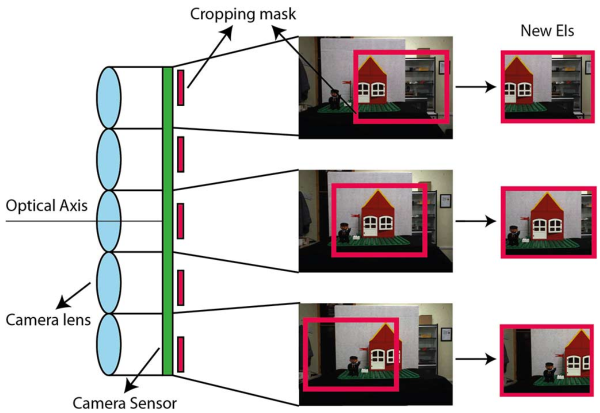


Fig. 1. Illustration of the cropping procedure. Note that the position of the cropping mask depends on the relative position of the EI in the integral photography. After cropping, a new set of EIs is generated.

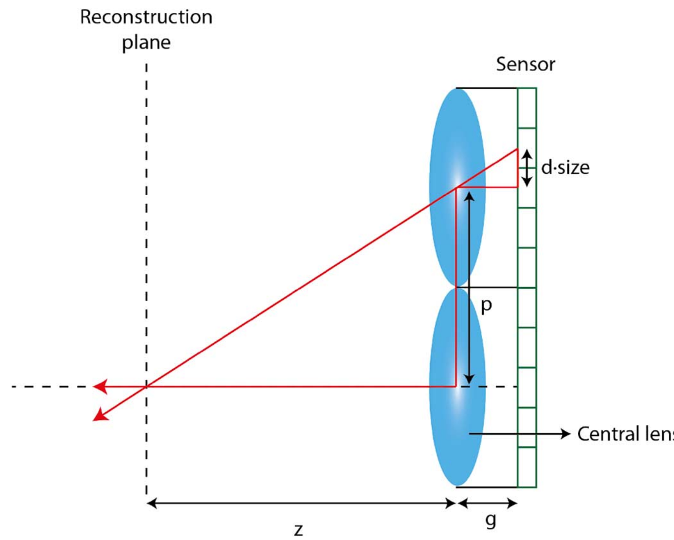


Fig. 2. Relation between the shift in pixels of the cropping mask and the reference plane. In the figure, d is the shift in pixels, g is the gap between lens and sensor, and p is the pitch of the lenses or the axial separation between cameras and size is the size of the pixels.

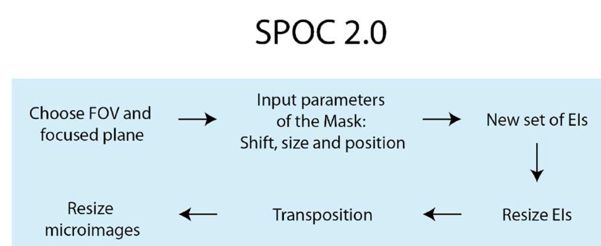


Fig. 3. Workflow diagram of the SPOC 2.0 algorithm: 1. Choose FOV and focused plane, 2. Input the parameters of the cropping mask, 3. Apply the mask, 4. Resize the new EIs, 5. Apply transposition, 6. Resize microimages.

calculated frames are ready for their projection onto an IP monitor with the aim of displaying 3D scenes with full parallax. To this end, the SPOC 2.0 algorithm, which was proposed in our previous study [6], is updated to make easier the fluent tuning of the display parameters. The 3D travelling sequence generated is composed by a set of IP frames whose FOV, resolution and reference plane can be selected at will. In order to demonstrate the utility of our method, two experimental 3D travelling videos are generated. This paper is organized as follows: Section II is devoted to describe our proposal. In Section III, we show the experimental results. Finally, Section IV summarizes the main achievements of our research.

II. Methods

Let us start by making a short description of SPOC 2.0 algorithm, which is more carefully described and illustrated in [6]. The algorithm is mainly based in the fact that one can easily convert the information captured with an IP capture system, into the information that has to be projected on an IP monitor. Basically, the IP system captures and integral photograph, which is composed by few (typically 7×7, 11×11, or similar) EIs with high resolution (typically the resolution of a digital camera). This information has to be transformed in a collection of microimages. The number of microimages should be equal to the number of lenses that compose the MLA in the IP monitor. Also, any microimage should have a number of pixels equal to the number of pixels behind any microlens in the IP monitor. To make this transformation we simply need to transpose the angular and the spatial information in the integral photograph. To perform correctly the algorithm it is also necessary a cropping action, which is described below.

Since our final aim in this research is to display 3D images through an IP monitor, the process of capture of the integral photograph should be adapted to the monitor characteristics. In this sense, the first parameter of interest is the number of pixels behind any microlens in the IP monitor. Due to the transposition relation, the number of EIs should be equal to the number of pixels per microimage. If these two numbers do not match, an interpolation process would be required, which could reduce the quality of the displayed images. Since, in our experiments, we will use the synthetic aperture method, in which all the EIs are picked up with only one digital camera that is mechanically displaced, there is no problem to fulfill this requirement.

The next step is to crop the EIs. Specifically, the magnitude and format of the cropping determines the FOV and format of the displayed images. If the EIs are cropped in rectangular 3×4 format, the displayed images will have also 3×4 format. On the other hand, the smaller the cropping ratio (i.e. the quotient between size of cropped EIs and original EIs) the smaller the FOV of the displayed images and therefore the feeling of foreground. Besides, the position of the center of the central mask determines the center of the FOV of displayed 3D images.

The second parameter of interest in the cropping is the selection of the reference plane (i.e. the plane that, when the image is displayed, is reconstructed at the plane of the monitor). Other planes of the scene are displayed either in front or behind the monitor. If the cropping masks are centered at the center of the original EIs, the reference plane is at the infinite. A centrifugal displacement of the cropping-masks proportional to the distance between the corresponding EI to the central EI, see Figs. 1, permits to bring nearer the reference plane, see Fig. 2 and 4. Then, the continuous tuning of the cropping parameters results in a fluent change of the in-focus plane and the FOV of the displayed image. So, each time this algorithm is executed using the same

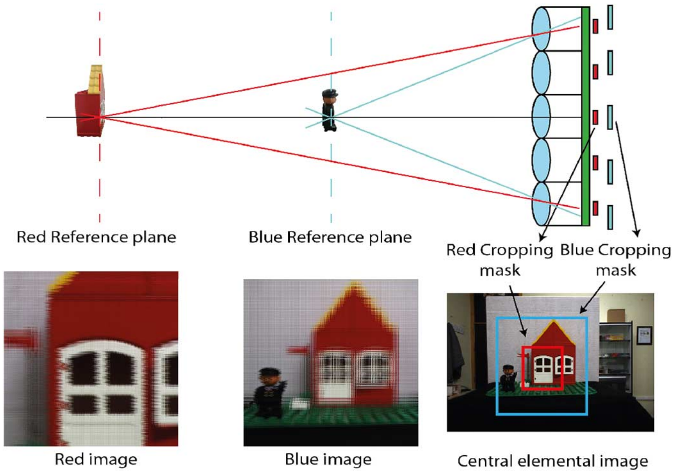


Fig. 4. Illustration to show how the change of the size and position of the cropping mask in each elemental image modifies the FOV and the reference plane. The more the cropping mask is separated from the center of the EIs the closer the position of the reference plane is (see the red and blue cropping mask examples).

Fig. 5. Disparity map obtained from two EIs of the integral photography using the SAD method. It is possible to distinguish different objects of the scene. In addition, knowing the parameters of the capture permits to obtain the depth information of the scene.

Fig. 6. 3D scene used as the object for our first experiment.

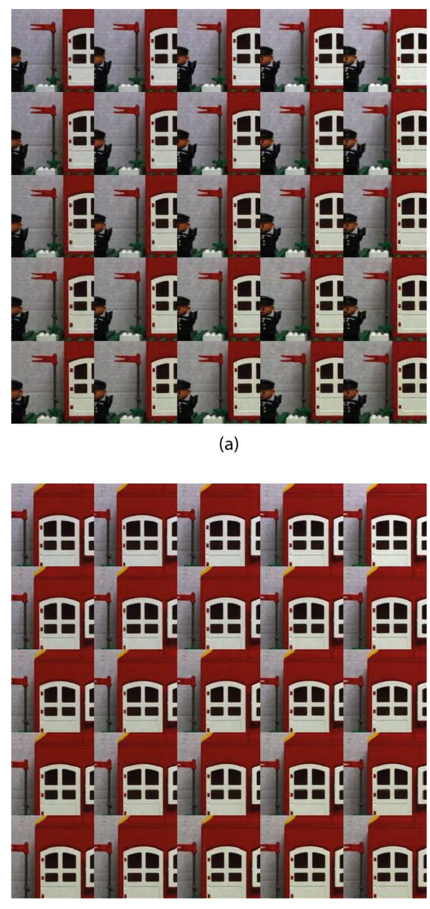


Fig. 7. 5 × 5 elemental images captured by implementation of the synthetic aperture procedure.

integral photograph, as the input, but different cropping parameters, a different collection of microimages is generated. By performing this procedure several times, a stack of different microimage sets is obtained. Finally, we compose a video whose frames are the stack of microimages generated. After projecting this video onto the IP monitor, the travelling 3D scene is displayed with full parallax.

The flowchart of the SPOC 2.0 algorithm is shown in Fig. 3. As explained above, in a first step a new set of synthetic EIs is obtained after applying the cropping procedure. In the second the microimages are calculated from the new synthetic EIs, by simply transposing angular and spatial information. The generated microimages are ready to be projected onto the IP monitor.

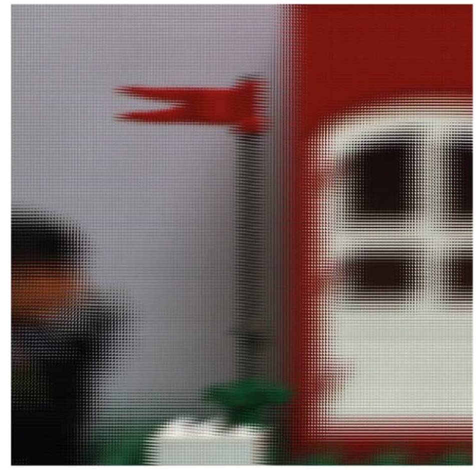
There are two issues to look after when applying SPOC 2.0: the parameters of the cropping mask and the resizing of images. The first issue have been already discussed: the size and position of the cropping mask define the characteristics of the displayed 3D image, as can be seen in Fig. 4. The second issue is the resizing of calculated microimage sets, in order to adapt the resultant images to the IP monitor. The algorithm applies a resize twice during its execution. First, before applying the transposition, each EI is resized so that they have a number of pixels equal to the number of microlenses used in the IP monitor. Second, another resize is applied to the calculated microimages, so that each has a number of pixels equal to the number of pixels behind any microlens of the IP monitor. In this last process, there is no need of rounding.

Next we explain the update we have introduced on the SPOC 2.0 in order to allow the automatic computation of the travelling frames. Note that for the application of the SPOC 2.0 the position of the reference plane for any frame must be

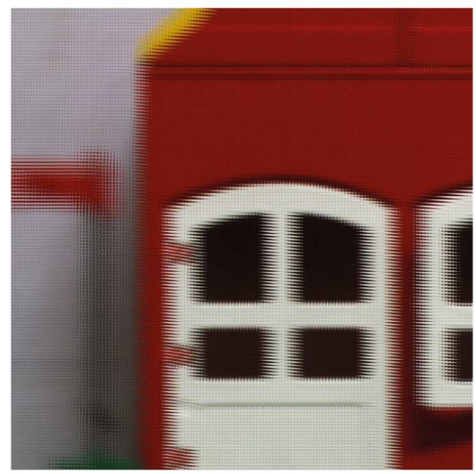
(a)

(b)

Fig. 8. Synthetic EIs generated after the cropping procedure, with cropping ratio 0.4 (a) Reference plane and FOV centered at the flag. (b) Reference plane and FOV centered at the door.



(a)



(b)

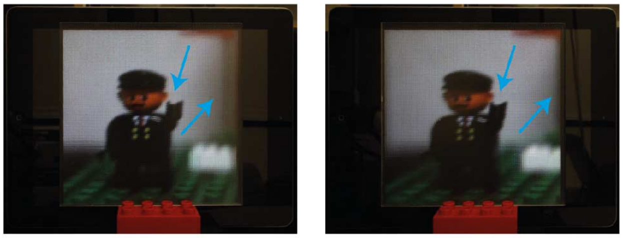
Fig. 9. Frames calculated from the integral photograph in Fig. 7. The frames were calculated by transposition between angular and spatial content. In MEDIA1we show a whole movie composed by 126 frames in which it is synthesized the travelling movement of a cameraman through the 3D scene.

accurately determined. To this end we added to our algorithm a routine for the calculation of a disparity map from two of the original EIs. This map permits to identify the objects at different depths. As an example, in Fig. 5 we show the disparity map of our 3D scene. This map was calculated by the SAD (Sum of Absolute Differences) method. From the disparity map, it is easy to calculate the (x,y,z) position of any object of the 3D scene.

III. Experimental Results

To illustrate our method we first captured, by the synthetic aperture method [24], a collection of 11 $\times$ 11 EIs of the 3D scene shown in Fig. 6. The distance between the camera and the first object was 39 cm and the scene total depth, from the doll to the background, was 16 cm. The camera used in the experiment (Canon, 450D) was assembled with an 18–55 mm objective. The lateral shift between neighbor EIs was 6 mm, the focal length of the camera was adjusted to 18 mm and the reference plane was placed at infinity. In Fig. 7 we show a subset of the integral photograph composed by 5 $\times$ 5 captured EIs. The goal of the experiment is to use these EIs as the input for our algorithm and therefore to calculate the microimages corresponding to any frame of the travelling movie. To this end it is necessary to perform, frame by frame, the cropping procedure. As an example we show in Fig. 8 two sets of cropped EIs. Specifically, the cropped EIs in Fig. 8(a) were calculated after fixing the desired FOV and the reference plane at the flag. The EIs in Fig. 8(b) were calculated by fixing the FOV and the reference plane centered at the door.

Note that the microimages, obtained after the application of the complete SPOC 2.0 process, should be properly adapted to the IP monitor parameters. In our case, the IP monitor was built by using an iPad with retina display and an array of microlenses whose pitch and focal length are, respectively, 1.0 and 3.3 mm. The number of pixels behind each microlens is, then, 10.39 $\times$ 10.39. Thus, any calculated integral photograph should be composed by 11 $\times$ 11 EIs, each resized to 147 $\times$ 147 pixels. To calculate the travelling frames through the 3D scene, the FOV and reference plane of the generated microimages need to match with the characteristics and movement of the simulated camera. In our case, after applying the second step of SPOC 2.0, we calculated 126 frames, tuning the size and center of the FOV and the reference plane in each one. With the frames we composed a video, MEDIA1. Two frames of this video are shown in Fig. 9.



(a)

(b)

Fig. 10. Frames of the movie obtained by recording the IP monitor from a given distance, 50 cm, but changing the viewing angle: (a) the FOV and reference plane is centered at the doll. (b) the FOV shows the whole scene and the reference plane is at the house plane. In both cases, there are two images that show the end left and the end right views respectively and arrows pointing the parallax differences. The movie is shown in MEDIA2.

In the final part of our experiment we projected the video on our IP monitor, which, therefore, displayed a whole 3D traveling sequence. Note that at every frame of such displayed movie the parts of the scene reconstructed in front, at or behind the screen change when the reference plane changes. To show this effect, we have composed a new movie obtained by recording the IP monitor from a given distance, 50 cm approximately, while changing the viewing angle. This movie is shown in MEDIA2. Note that in MEDIA2 we stop the travelling in three moments in order to show the parallax of the displayed images. Besides, in Fig. 10 we show four frames extracted from the video. While in panel (a) of Fig. 10 the FOV and reference plane are centered at the doll, in panel (b) the FOV covers the whole 3D scene and the reference plane is at the house plane. Besides, for both cases we show two different views of the scene. Also, we added arrows pointing the parallax differences.

To finish this section we performed a second experiment, aiming to show that the method can also be applied to an IP video. This means that we can capture a video of a 3D scene in motion, and apply our method to provide extra travelling effect. In our experiment we recorded a set of 12 integral photographs in which the position of the doll was changing. To reduce in this preliminary experiment the time and effort of the recording stage, each integral photograph is composed only by 5×5 EIs. Since we want to follow the trajectory of the doll, the FOV and reference plane of the generated images are always centered at the doll plane and, consequently, only one collection of microimages is generated from each integral photograph. After applying the whole process a video of microimages composed by 12 frames was obtained, see MEDIA3. To project this video onto the IP monitor the microimages were resized from 5×5 to 10.39×10.39 pixels. Again, to demonstrate the 3D nature of the displayed images we have recorded a video, with a camera placed in front of the IP monitor. Four different frames of this video are shown in Fig. 11. The whole video is collected in MEDIA4. It is worth to mention that the scaling process is performed via computational methods and, therefore, it does not introduce new information. This means that the quality of the resized microimages is worse that the quality of the microimages when they are properly fitted to the integral imaging monitor.

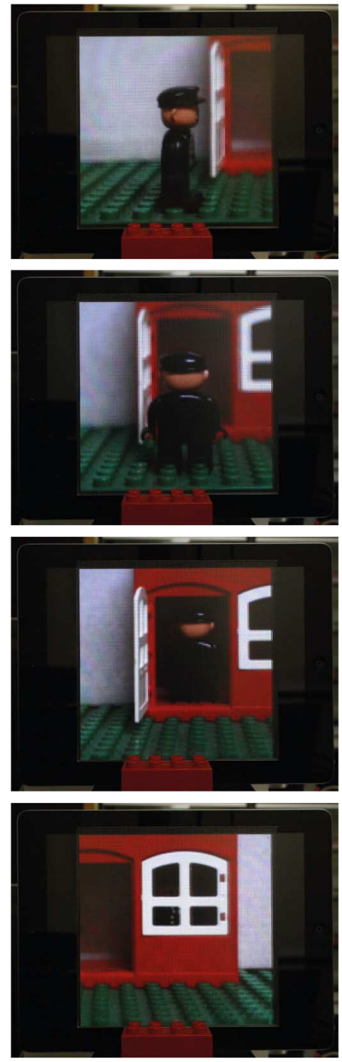


Fig. 11. Frames of the projected IP video traveling. See that the camera follows the human toy movement through the scene. The traveling movie can be seen in MEDIA3, and when the movie is projected into the iPad MEDIA4

IV. Conclusion

In this work, we propose a computational method to generate a 3D traveling video from a single integral photograph. The proposed method is the following. From the captured integral photograph, first we calculate a disparity map. Using this map, we can identify different objects at different depths. Then we apply the SPOC 2.0, as many times as frames we want in the video, and generate a set of images with different FOV and reference plane. Finally we compose a movie, which simulates a camera traveling through the scene, with the calculated frames and display the video in the IP monitor. This procedure can also be applied to the frames of an IP video. This method can help to alleviate the need for huge amount of data typically associated to any 3D movie.

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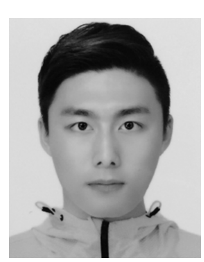

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