Invited Paper

Free segmentation in rendered 3D images through synthetic impulse response in integral imaging

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ABSTRACT

Integral Imaging is a technique that has the capability of providing not only the spatial, but also the angular information of three-dimensional (3D) scenes. Some important applications are the 3D display and digital post-processing as for example, depth-reconstruction from integral images. In this contribution we propose a new reconstruction method that takes into account the integral image and a simplified version of the impulse response function (IRF) of the integral imaging (InI) system to perform a two-dimensional (2D) deconvolution. The IRF of an InI system has a periodic structure that depends directly on the axial position of the object. Considering different periods of the IRFs we recover by deconvolution the depth information of the 3D scene. An advantage of our method is that it is possible to obtain non-conventional reconstructions by considering alternative synthetic impulse responses. Our experiments show the feasibility of the proposed method.

Key words: 3D image processing, Image reconstruction algorithms, 2D deconvolution.

Integral imaging is a technique based on the original idea proposed by Lippmann in 1908 [1]. To record a set of different perspectives of a 3D scene, i.e. a set of elemental images (EIs), a microlens array (MLA) is placed in front of a camera sensor. Because each microlens separates the rays to impact into different positions on the sensor array, both the spatial and also de angular information of the scene are captured by the system [2,3]. The original application of InI was related with the autostereoscopic display, and has been intensively developed during last years to produce a 3D image that can be visualized without the need for any special glasses [4-6]. However, display is not the only important application of InI technique [7-12]. The recover of the depth information of a 3D scene can be achieved from a single capture [13,14] by computationally projecting every EI through a virtual pinhole array or, equivalently overlapping and summing the intensities of the different elemental images [14]. Based on this principle, many digital reconstruction algorithms have been proposed [15-20]. Here, we have developed a new free depth-reconstruction method based on 2D deconvolution between the integral image capture in an InI setup and the corresponding IRF. By changing the period of the impulse response it is possible to select the appropriate depth of the reconstructed images. We also show that one can perform alternative reconstructions by considering non-conventional impulse responses.

Let us start by describing the capture process of an InI system. As we can see from Fig. 1, each microlens of the MLA images the 3D object providing a 2D image on the CCD plane. Consider only one point of the 3D object. From Fig. 1 it is easy to see that the image recorded by the sensor camera has a periodic structure, so we can express the impulse response function (IRF) of the system as a comb function of period $p(z)$, being

$$p(z)=d\left(1+\frac{g}{z}\right) . \tag{1}$$

Note that the period of the IRF is related with the axial position z of the point source and therefore, the further the ob-

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ject from the MLA, the smaller the period of the IRF.

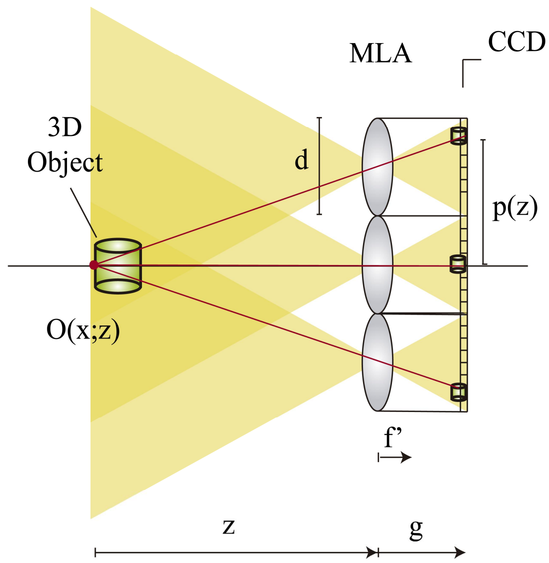

Fig.1. Capture process of an InI system. The diameter and focal length of each microlens are d and f', respectively. The CCD plane is placed at a distance g from the microlenses.

Considering that our system is 2D linear and shift invariant (LSI) and without taking into account the diffractive effects, we can write the impulse response function $h(\mathbf{x};\mathrm{z})$ as

$$h(\mathbf{x};\mathrm{z}) = \sum_{\mathrm{m_x}} \sum_{\mathrm{m_y}} \delta\left(\mathbf{x} - \mathbf{m}p(\mathrm{z})\right) , \tag{2}$$

where the symbol δ represents the Dirac delta function. In Eq. 2 we have considered that the microlenses are centered at positions $\mathbf{x} = \mathbf{m}p$, being $\mathbf{m} = (\mathrm{m_x}, \mathrm{m_y})$ the microlens index in both directions, x and y.

If $O(\mathbf{x};\mathrm{z})$ is the intensity distribution of a plane of the 3D object located at a distance z (see Fig. 1), then the intensity distribution $I(\mathbf{x};\mathrm{z})$ at the CCD plane can be written as

$$I(\mathbf{x};\mathrm{z}) = \frac{1}{M_z^2} O\left(\frac{\mathbf{x}}{M_z}; \frac{\mathrm{z}}{M_z^2}\right) \otimes_2 h(\mathbf{x};\mathrm{z}) , \tag{3}$$

where we have made use of the 2D convolution function between the object scaled with lateral magnification $M_z = -g/z$ and the IRF.

For our purpose we will consider the particular case in which the whole 3D scene is composed by a discrete number of planes. The total intensity distribution at the sensor plane is then

$$I(\mathbf{x}) = \sum_{n=1}^{N} I(\mathbf{x}; z_n) , \tag{4}$$

where $I(\mathbf{x}; z_n)$ are the intensity distributions associated to each section of the scene. Note that due to the periodicity of the IRF, the integral image registered by the sensor will be composed by a set of replicas of the different plane objects. Also, because each plane is located at a different position on the optical axis, the spatial shifting of the replicas will have a different period.

From an integral image obtained by an InI system like the one described before, we are interested in extracting the depth information and performing the refocus of the 3D scene. Suppose that we want to extract the depth information of the plane characterized by $n=1$. We represent the optical transfer function (OTF) of the system as $H(\mathbf{u};z_n)$. Then, we perform the following operation

$$\tilde{I}_R(\mathbf{u}) = \frac{\tilde{I}(\mathbf{u})\,\hat{H}^*(\mathbf{u};z_1)}{\left|\hat{H}(\mathbf{u};z_1)\right|^2 + w^2}\ , \tag{5}$$

with

$$\tilde{I}(\mathbf{u}) = \sum_{n=1}^{N} \tilde{O}\left(M_{z_n}\mathbf{u}; \frac{z_n}{M^2_{z_n z_n}} \right) \cdot H(\mathbf{u};z_n)\ . \tag{6}$$

In Eqs. 5-6 the symbol ~ is used to represent the 2D Fourier transform operation, * represents the complex conjugation, and $\mathbf{u}=(u,v)$ are the spatial frequencies. From Eq. 5 we can realize that this operation represents a Wiener filter (being w^2 the Wiener parameter [21]) over the spectrum of the integral image $\tilde{I}(\mathbf{u})$ and the computed transfer function $\hat{H}(\mathbf{u};z_1)$ for the plane $n=1$. By combining Eq. 5 and Eq. 6, we obtain that

$$\tilde{I}_R(\mathbf{u}) = \tilde{O}\left(M_{z_1}\mathbf{u}; \frac{z_1}{M^2_{z_1}} \right) + \frac{\sum_{n=2}^{N} \tilde{O}\left(M_{z_n}\mathbf{u}; \frac{z_n}{M^2_{z_n}} \right) \cdot H(\mathbf{u};z_n)\,\hat{H}^*(\mathbf{u};z_1)}{\left|\hat{H}(\mathbf{u};z_1)\right|^2 + w^2}\ . \tag{7}$$

Finally, performing the Inverse Fourier transform of Eq. 7, we have

$$I_R(\mathbf{x}) \simeq O\left(\frac{\boldsymbol{x}}{M_{z_1}}; \frac{z_1}{M^2_{z_1}} \right) + \sum_{n=2}^{N} O_{z_n}\left(\frac{\boldsymbol{x}}{M_{z_n}}; \frac{z_n}{M^2_{z_n}} \right) \otimes h'(\boldsymbol{x};z_1)\ , \tag{8}$$

that represents the reconstruction in the selected plane of the 3D scene. In Eq. 8, the term $h'(\boldsymbol{x};z_1)$ represents the information of all the planes of the 3D scene that are out of focus, or in other words, the planes for which $z \neq z_1$. Note that we have considered a proper signal-to-noise ratio which implies that we can neglect the term w^2 when we compare it with the OTF associated to $z = z_1$.

Now, we are interested in verifying our method. For this proposal, we registered the integral image shown in Fig. 2(a). The integral image is composed by a set of 3x3 EIs, with 600x600 pixels each (Fig. 2(b)). To carry out the capture process, we used the synthetic aperture method [22], in which a digital camera is translated a distance of 50 mm along the directions x and y in order to capture the different perspectives of the 3D scene. The camera used in this experiment was a Canon 450D assembled with an EFS 18-55 mm lens. As we can see from Fig. 2, the two objects used for the capture experiment were placed at different depths so the periodicity of these two objects in the integral image is different, according to Eqs. 1-3.

The first step to depth-reconstruct the 3D scene is to create the different IRFs of our system. Note that due to the finite number of pixels of the camera sensor, there will be only a finite number of impulse responses. In fact, this is the reason why we only will be able to reconstruct a discrete number of planes within the 3D scene. The second step is to calculate the spectrum of both, the integral image and the impulse responses. Now, we apply the proposed deconvolution algorithm from Eq. 5 and, after Inverse Fourier transforming we obtain a set of depth-reconstructed images. All our algorithms were implemented using Matlab©.

In Fig. 3 we can see how we can select the plane of the 3D scene that appears in focus. To obtain the reconstruction shown in Fig. 3(a) we consider an IRF with a periodicity of 485 pixels, whereas for Fig. 3(b) the periodicity of the impulse response was 535 pixels.

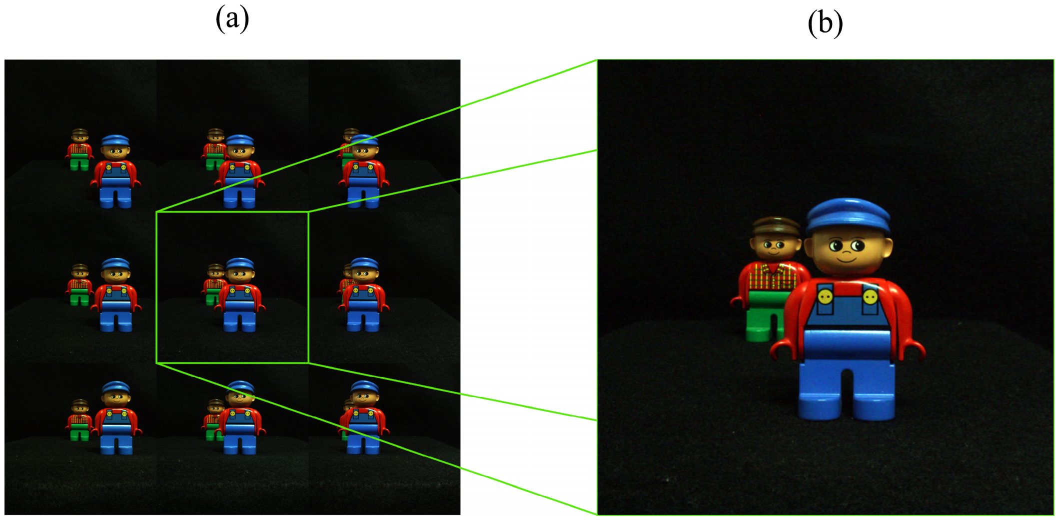

Fig. 2. (a) Integral image captured with the synthetic aperture method. (b) Central elemental image from (a).

The main advantage of our method is that it works in the Fourier domain, so it allows us to perform a variety of digital processing that would be impossible to carry out otherwise in integral imaging. In Fig. 4 we can see an alternative reconstruction in which we focus simultaneously two different planes of the scene. In this case, the synthetic impulse response used in the deconvolution algorithm is a combination of the two individual IRFs associated with each plane in focus. As a result, we see from the figure that we can extend the depth of field of the reconstruction.

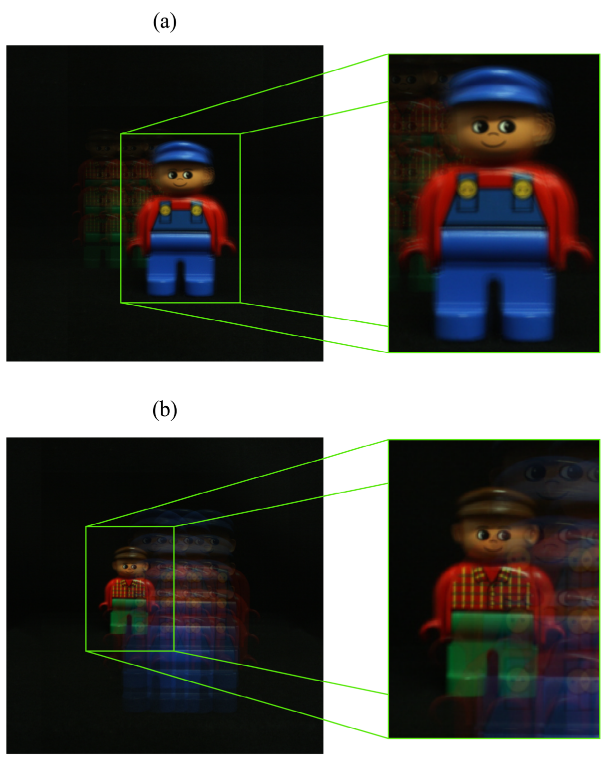

Fig. 3. Two planes of reconstruction from the integral image shown in Fig. 2. The depth reconstruction is achieved after applying our deconvolution algorithm.

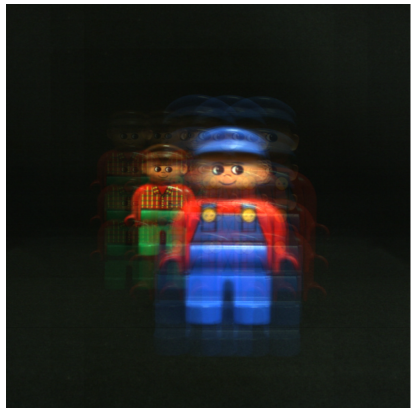

Fig. 4. Alternative depth-reconstruction from our integral image. Note that we focus simultaneously the two objects of the 3D scene.

In this contribution we have presented a novel method to recover the depth information in InI. Although our algorithm is based on 2D deconvolution and it works in the Fourier domain, it has been demonstrated that resolution of the reconstructed images is equivalent to resolutions obtained with the conventional methods which work in the spatial domain [23], being even within the theoretical prediction [24].

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