Non-Homogeneity of Lateral Resolution in Integral Imaging

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***Abstract*—We evaluate the lateral resolution in reconstructed integral images. Our analysis takes into account both the diffraction effects in the image capture stage and the lack of homogeneity and isotropy in the reconstruction stage. We have used Monte Carlo simulation in order to assign a value for the resolution limit to any reconstruction plane. We have modelled the resolution behavior. Although in general the resolution limit increases proportionally to the distance to the lens array, there are some periodically distributed singularity planes. The phenomenon is supported by experiments.**

***Index Terms*—Three-dimensional (3D) imaging, lateral resolution, depth of field.**

I. Introduction

INTEGRAL IMAGING (InI) is a well-established technology for the recording, processing and display of 3D incoherent images. Based on the original idea of Lippmann [1], InI systems capture the information of 3D scenes by use of a microlens array, which permits the recording of multi-perspective information on an image sensor. Being a technique for the 3D reconstruction and/or display of 3D scenes, the evaluation of the lateral resolution at different depths is a matter of great interest.

Integral imaging was originally designed for the auto-stereoscopic display of 3D objects. Even at present this is a fascinating application [2]–[8]. To implement an InI monitor it is necessary to project the elemental images onto an electronic matrix display (like LCD or LED). The microlens array (MLA) is adjusted so that each microlens covers one elemental image. In this case the different perspectives are integrated as a 3D image. Every pixel of the display generates a cylindrical ray bundle when it passes through the array. The intersection of the ray bundles produces a local increment of light density, which permits the reconstruction. The resulting reconstructed scene is perceived as 3D by the observer, whatever his or her position relative to the MLA. Since an InI monitor truly reconstructs the 3D scene, the observation is produced without special goggles, with full parallax, and with no visual fatigue. To ensure that the displayed 3D images are observed with continuous relief, it is necessary to adjust the system in such a way that the display device is set at the front focal plane of the microlenses and only one pixel is seen through any lens [9]. In such case the display resolution unit (DRU) is the microlenses pitch [10]–[12]. Thus, the way to improve the resolution of InI monitors is by use of MLA with smaller pitch. Of course, this implies the use of display devices with increasing density of pixels, since the number of pixels under any microlens determines the angular resolution of the display.

Although originally intended for display, InI technology has revealed as useful for other applications [13]–[19]. One of the most important features of InI systems is their ability for reconstructing in depth, the irradiance distribution of the 3D scene [20]. This ability can be easily understood if one consider that any elemental image constitute a low-NA image of the 3D object. Note that low-NA images inherently have large depth-of-field (DOF). However the composition of all the elemental images behaves as a high-NA image, which inherently has short DOF. Thus, by projecting (computationally) all the elemental images through virtual pinholes placed at the center of the corresponding microlenses, it is possible to obtain the depth reconstruction. At any plane the reconstruction is composed by a sharp image of the part of the scene in that plane, plus the blurred image of out-of-focus parts. Due to the high-NA behavior of the systems, out-of-focus images are so blurred that they are difficult to distinguish and mainly constitute a background. This high capacity of segmentation in depth confers the InI technique great potential for scientific applications. For this reason the study of the resolution of reconstructed integral images is a matter of great interest. This ability has been analyzed in terms of the lateral and axial resolution [21]–[25]. Subsequent investigations have led to consider the lateral resolution as function of the distance between the reconstruction plane and the microlenses.

In this paper, we tackle the analysis of the lateral resolution on the basis of the concept of sampling ray. Sampling itself is basically the process of projecting rays from any pixel of the sensor through the center of its associated microlens into the scene. These rays intersect the surfaces of the objects contained in the volume of the scene, and each ray transfers the object information to its corresponding pixel. As a result of the complexity of the lattice generated by the collection of all generated sampling rays, the lateral resolution of the system is neither homogeneous nor isotropic.

The paper is organized as follows. In Section II, we expose the basic theory that is behind the capture and reconstruction

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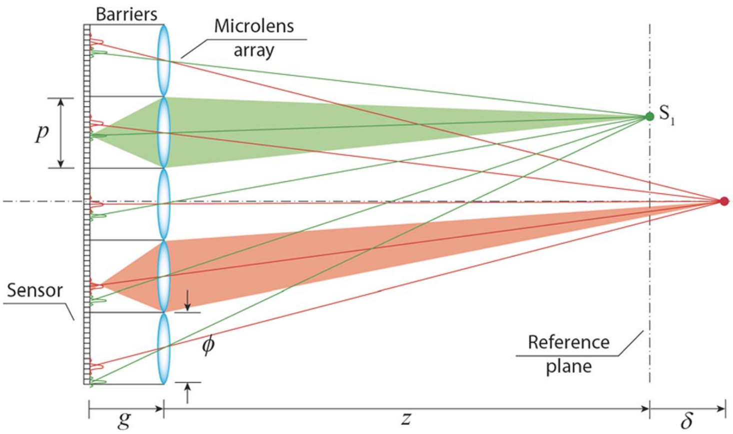

Fig. 1. Capture stage of an InI system.

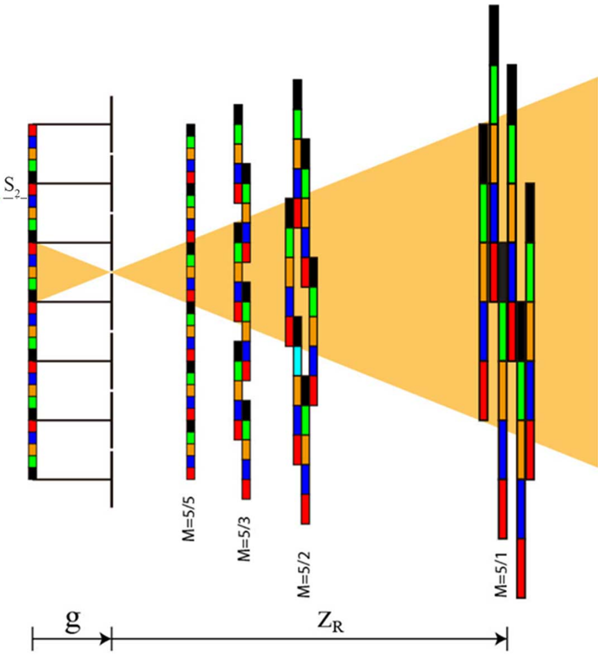

Fig. 2. Scheme of the conventional reconstruction algorithm. In this figure, the number of pixels per microlens is $N = 5$.

stages. In Section III, we present our model for the evaluation of the lateral resolution at different reconstruction planes. In Section IV, we apply our model to different InI configurations and find the quasi-periodical evolution of the lateral resolution. In Section V, we validate the model with experimental results. Finally, in Section VI, we summarize the achievements of this research.

II. Basic Theory

InI is based on the two stages of optical capture and numerical reconstruction. In the capture stage the image sensor is set parallel to the microlens array (MLA) at a certain position near the focus, so that a certain plane of the scene, which we will call reference plane, is conjugated with the sensor (see Fig. 1). By application in cascade of paraxial scalar diffraction equations [27], it is straightforward to find the impulse response of a single microlens. For simplicity we consider quasimonochromatic illumination with mean wavelength λ. Assuming that the pupil of each microlens is a circle with diameter ϕ, we can express the intensity distribution over the sensor plane as

$$H_\lambda(r,z) = \left| \int_0^{\phi/2} p(r_0) \exp\left\{ i\frac{\pi}{\lambda} \frac{z}{z(z-\delta)} r_0^2 \right\} \times J_0\left(2\pi \frac{r r_0}{g}\right) r_0 dr_0 \right|^2 \quad (1)$$

This function accounts for the microlenses pupil function, $p(r_0)$, together with the phase modulation due to defocus. Any point of the scene produce in the sensor a signal that is not a point but a diffraction pattern, or intensity patch. If the pixel size of the sensor is smaller than the size of such pattern, more than one pixel will be excited. Points contained in the reference plane ($\delta = 0$) are imaged onto the sensor as an Airy disk. Points of the scene not in the conjugate plane ($\delta \neq 0$) produce a signal in the form of a defocused Airy disk, which is broader than the Airy disk, and therefore the number of recorded pixels is higher.

Thus, a point object produces onto the sensor a 2D array of, focused or blurred, Airy disks. Due to the presence of the barriers, which prevent from the overlapping between neighbor elemental images, the number of recorded Airy disks is limited.

Note that whereas, both, the microlenses and the pixels behind them are arranged in rectangular grid, the Airy disk shows radial symmetry. This constitutes the first cause of anisotropy in the InI systems. Moreover, the capture stage is not shift invariant. A lateral displacement of the point object does not imply a proportional shift of the signal received by the sensor. Due to the necessary presence of the barriers, as the point source is laterally shifted, some elemental images switch off and some other switch on.

The numerical reconstruction can be made by use of different algorithms. However, all are based on the same principle of projecting any elemental image through a pinhole placed at the center of the corresponding microlens, as shown in Fig. 2. From the scheme, we can see that there is a univocal relation between the position of the reconstruction plane and the level of overlapping between projected elemental images. Specifically, the relation is

$$M = \frac{z_R}{g} = \frac{N}{N-n} \quad (2)$$

where N is the number of pixels per microlens and n the number of pixels that overlap with the neighbor projected elemental image. It is apparent that the higher the level of overlapping, the smaller the number of pixels of reconstructed images. To avoid unbalanced values of pixels of reconstructed images, the value of the pixels should be normalized taking into account the number of projected pixels that contribute to any reconstructed pixel. In planes where the projected pixels do not match (i.e., in case of non-integer value of n) it is also possible to calculate the reconstruction. But the algorithm is slower, since it has to evaluate the percentage of contribution of any projected pixel to the pixels of the reconstructed images.

Naturally, the algorithm that we are reporting here must take into account not only the pixilated structure of the sensor, but also the diffraction effects. A scheme of this is shown in Fig. 3, for the case of a two-point object.

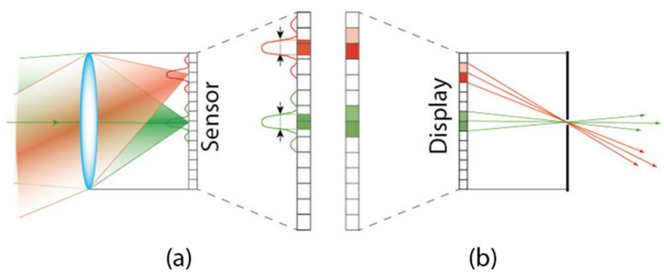

Fig. 3. (a) Intensity distribution over the image sensor for an elemental image; (b) Projection of the recorded pixels in the reconstruction stage.

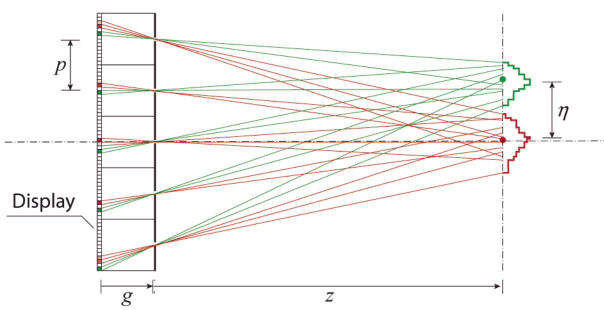

Fig. 4. Scheme of the numerical reconstruction algorithm.

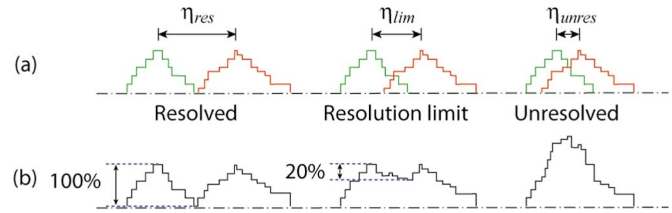

Fig. 5. Resolution criterion. (a) Projection of elemental images corresponding to two point sources; (b) Irradiance pattern resulted from the sum of individual projected diffraction patterns.

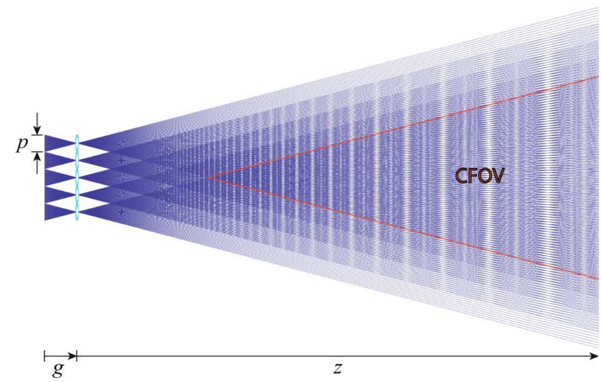

Fig. 6. Sampling ray pattern generated by an InI capture system and its common field of view.

III. The Lateral Resolution

The lateral resolution of numerically reconstructed depth images depends on many factors, such as the number of microlenses, the number of pixels per microlens, the gap, the pitch, the distance between the reconstruction plane and the reference plane, and also on the diffraction effects. As in conventional imaging, we will evaluate the lateral resolution in terms of the Rayleigh resolution criterion.

As sketched in Fig. 4, the reconstructed image corresponding to two point sources is obtained after virtual projection of the recorded pixels through the pinholes. Note that the projections have a stair case form.

Following Rayleigh, we propose to define the resolution limit as the minimum distance, $\eta_{\rm lim}$, between the projected pixilated diffraction patterns so that the dip between them is larger that 20% of the maximum peak (see Fig. 5).

The Rayleigh limit was thought for imaging systems that are, at least locally, linear and shift invariant. However, the reconstruction process in InI is not shift invariant. Depending on the lateral position of the object the resolution can change significantly. Moreover, even after fixing the position of the object, the resolution strongly depends on its angular orientation. This is due to the disadjustment between the radial symmetry of the Airy disk and the rectangular arrangement of the microlenses and the pixels behind them. Thus a new model for the calculation of the resolution limit is required.

To face this task, we propose a model based on Monte Carlo simulations [26]. Specifically we proceed as the following. First, we determine the region in the reconstruction space covered by all the microlenses. This region is known as the common-field-of-view (CFOV) region, see Fig. 6. In this figure we can observe the existence of planes of low density of sampling rays, which are, precisely, the planes in which the projected pixels match (see Fig. 2). We will restrict the calculations of the resolution limit to this region. Second, we simulate the image capture stage as shown in the Fig. 1. Third, we obtain from the elemental images calculated in the previous step, the reconstructed images in discrete planes.

Since the lateral resolution is heterogeneous and anisotropic, we need to apply the Monte Carlo method to determine the resolution limit for any reconstruction plane. Thus, given a distance z, first we fix a value for distance η between the points (see Fig. 4). Then, we change randomly the position of the center of the two point sources and their angular orientation, up to 10^3 times. At any step we check if the two points are resolved (see Fig. 5). If the points are resolved for all steps, we decrease the value of η. Otherwise the distance is increased. The iterative process ends when the $\eta_{\rm lim}$ is reached with a tolerance of 0.4%. To validate our proposal, first we calculated the lateral resolution associated to some InI geometries. Later we confirmed these results with a laboratory experiment.

IV. The Numerical Evaluation

For the first numerical experiment we considered three different InI architectures. The architectures had in common the focal length $f_{\rm L} = 12$ mm, the $f_{\#} = 22$, and the pitch $p = 4.2$ mm, of the microlenses. The gap between the microlenses and the sensor was set to $g = 12.50$ mm, so that the reference plane was at $z = 300$ mm from the MLA. We also fixed the total amount of pixels of the sensor to about 2760×2760. The difference was the number of microlenses, and therefore the number of pixels per microlens. Specifically, we calculated the lateral resolution for the cases: (a) 11×11 microlenses and 251×251 px/microlens; (b) 21×21 microlenses and 131×131 px/microlens; and (c) 31×31 microlenses and

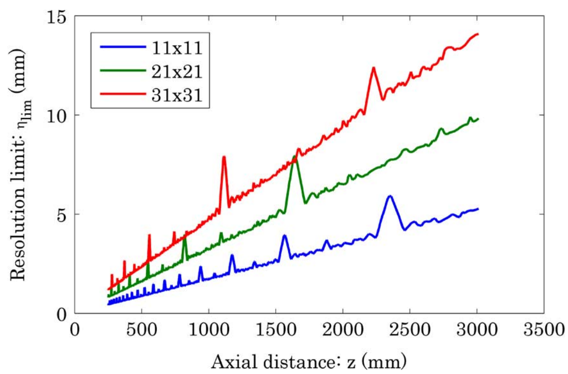

Fig. 7. Lateral resolution limit of reconstructed images versus reconstruction distance. In all cases the total number of pixels of the sensor are the same.

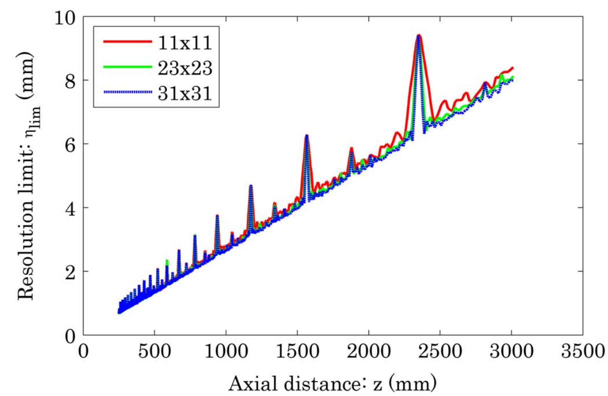

Fig. 9. Lateral resolution limit of reconstructed images versus reconstruction distance. In all cases the total number of pixels per elemental image are the same.

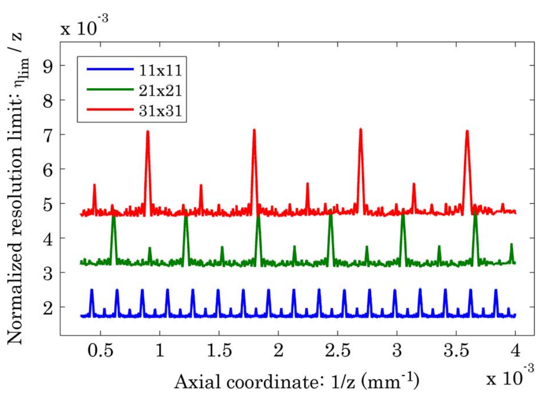

Fig. 8. Normalized resolution limit of reconstructed images versus the inverse of the reconstruction distance.

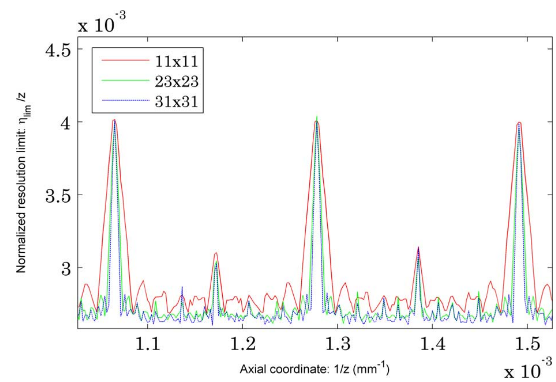

Fig. 10. Normalized resolution limit of reconstructed images versus the inverse of the reconstruction distance.

89×89 px/microlens. Concerning the reconstruction planes, we analyzed a range spanning from $z = 250$ mm to $z = 3000$ mm, with 1717 equal sampling distances in $1/z$. In Fig. 7, we show the computed values of the resolution limit. As expected, the general trend for the resolution limit is to increase proportionally to z. It is interesting, however, the existence of some peaks, which appear in the planes observed in [28] but were not accounted for. Note that the position of these planes coincides with the position of planes of low density of sampling rays (see Fig. 6).

An observation of the Fig. 7 tells us that the peaks are equidistant in $1/z$, and their height proportional to z. Then, it is more illustrative to make the representation in terms of a different scale, as shown in the Fig. 8. In this representation, we find a quasi-periodical structure of the resolution limit of reconstructed images in InI.

From the figures we can extract the following conclusions. First, the lateral resolution in the reconstructed images is determined, mainly, by the number of pixels of the elemental images. Second, incrementing the number of microlenses at the cost of reducing the number of pixels per microlens produces an important fall-off in resolution. Note however that this fall-off is compensated by the fact that the depth discrimination increases [25]. The resolution in the planes of low density of sampling rays is about 1.5 times worse than in the other planes. When represented in the proper space (see Fig. 8) the lateral resolution limit shows a quasi-periodical behavior. The period of such function is proportional to the number of microlenses.

To confirm these conclusions we performed a second numerical experiment. In this case, we kept constant the number of pixels per microlens, but variable the number of microlenses. Specifically we assumed microlenses of pitch $p = 10$ mm, focal length $f_L = 18.0$ mm and $f_\# = 22$. The gap was set to $g = 18.7$ mm and the number of pixels per microlens to 251×251. We calculated the lateral resolution for three arrays: (a) 11×11 microlenses; (b) 23×23 microlenses; and (c) 31×31 microlenses. The results are shown in the Fig. 9.

We found, again, that in trend the lateral resolution limit increases proportionally to the distance from the MLA to the reconstruction plane. Naturally, due to the heterogeneity and anisotropy of the process, there are fast variations over the general trend. Besides, there are some singular planes, the ones that correspond to the low density of sampling rays, in which the resolving power falls-off by a factor of about 1.5. To visualize the quasi-periodical variation of the lateral resolution limit, we use again the representation in the nonlinear space, but we concentrate the representation in only two periods of the function, see Fig. 10.

From the figure we confirm that, at least in terms of the lateral resolution of reconstructed images, increasing the number of microlenses does not improve significantly the efficiency of the system. The main improvement is the narrowing of the resolution-limit peaks. Since it is presumed that the increasing of the number of microlenses should imply an improvement of performance of InI systems, we will devote a further work to analyze, in terms of our statistical model, the influence of

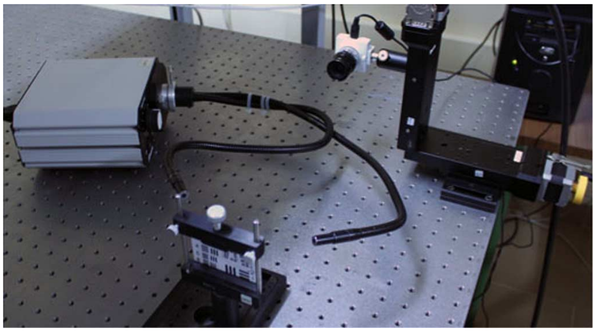

Fig. 11. Experimental setup.

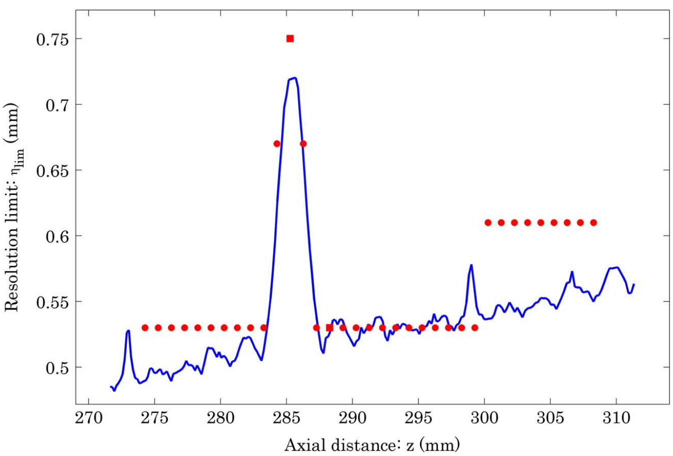

Fig. 12. Comparison between the experimental and the modelized values of the resolution limit. Note, that since the resolution is evaluated with an USAF test, only some quantized values of the resolution can be obtained.

these parameters on the depth discrimination of reconstructed images.

V. Experimental Verification

To verify our conclusions, we performed an InI experiment with the setup shown in Fig. 11.

Instead of using an array of microlenses, we used a synthetic aperture arrangement in which the digital camera, mounted in a motorized platform, was scanned following a rectangular grid. The object for the experiment was an USAF 1951 resolution chart. In our experiments, we obtained the integral images corresponding to 35 values of z, ranging from $z = 274.28$ mm to $z = 308.28$ mm. Each integral image was composed by 11×11 elemental images with 251×251 pixels each. As in the first numerical experiment, the pitch was fixed at $p = 4.2$ mm, the gap to $g = 12.5$ mm, and the $f_{\#} = 22$. For any of the recorded 35 integral images, we computed the corresponding reconstructed sectional images. With the USAF chart, we evaluated the lateral resolution limit associated to any of the 35 axial distances. These resolution values are presented in Fig. 12. As we see, the drastic fall-off in resolution predicted by our model, for some specific distances z, is fairly reproduced by the laboratory experiments.

Finally, in Fig. 13 we present two reconstructed images obtained in the vicinity of the resolution peak (square tags in the Fig. 12). Note that although the reconstruction plane at (z_2) is obtained further away from the sensor, the resolution is better. This fact confirms the existence of these resolution singularities.

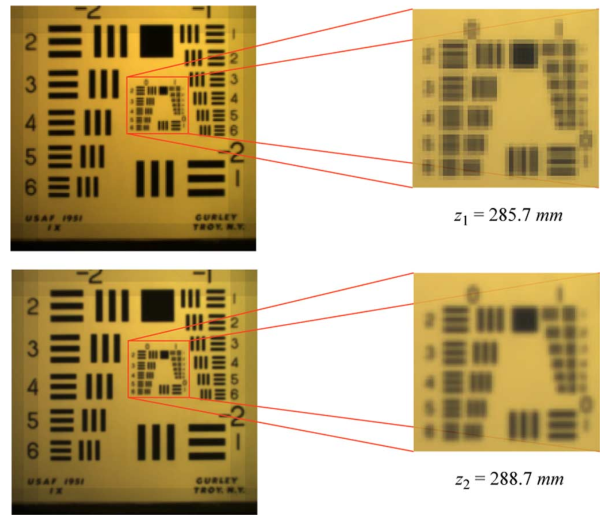

Fig. 13. Reconstructed images in planes near the resolution peak.

VI. Conclusion

In summary, we have presented a new procedure for the evaluation of lateral resolution in reconstructed InI scenes. The method takes into account both the diffraction effects in the image capture and the anisotropy and heterogeneity in the computational 3D reconstruction. The evaluation uses Monte Carlo simulations. We have found a periodicity in the behavior of the resolution limit, when plotted in a certain nonlinear representation. Our method has been validated with experimental results.

References

[1] G. Lippmann, "Epreuves reversibles donnant la sensation du relief," *J. Phys.*, vol. 7, pp. 821–825, 1908.
[2] S. W. Min, B. Javidi, and B. Lee, "Enhanced three-dimensional integral imaging system by use of double display devices," *Appl. Opt.*, vol. 42, pp. 4186–4159, 2003.
[3] B. Javidi, F. Okano, and J.-Y. Son*, Three-Dimensional Imaging, Visualization, and Display Technology*. New York: Springer, 2008.
[4] M. Miura, J. Arai, T. Mishina, M. Okui, and F. Okano, "Integral imaging system with enlarged horizontal viewing angle," in *Proc. SPIE*, 2012, vol. 8384, p. 838400.
[5] J. Arai, F. Okano, M. Kawakita, M. Okui, Y. Haino, M. Yoshimura, M. Furuya, and M. Sato, "Integral three-dimensional television using a 33-Megapixel imaging system," *J. Display Technol.*, vol. 6, no. 10, pp. 422–430, Oct. 2010.
[6] A. Özgür-Yöntem and L. Onural, "Integral imaging using phase-only LCoS spatial light modulators as fresnel lenslet arrays," *J. Opt. Soc. Amer.*, vol. A28, pp. 2359–2375, 2011.
[7] H. Liao, T. Dohi, and K. Nomura, "Autostereoscopic 3D display with long visualization depth using referential viewing area-based integral photography," *IEEE Trans. Visual. Comp. Graph.*, vol. 17, pp. 1690–1701, 2011.
[8] M. Martínez-Corral, H. Navarro, R. Martínez-Cuenca, G. Saavedra, and B. Javidi, "Full parallax 3-D TV with programmable display parameters," *Opt. Photon. News*, vol. 22, no. 12, p. 50, 2011.
[9] H. Navarro, R. Martínez-Cuenca, A. Molina-Martín, M. Martínez-Corral, G. Saavedra, and B. Javidi, "Method to remedy image degradations due to facet braiding in 3D integral imaging monitors," *J. Display Technol.*, vol. 6, no. 10, pp. 404–411, Oct. 2010.
[10] H. Hoshino, F. Okano, H. Isono, and I. Yuyama, "Analysis of resolution limitation of integral photography," *J. Opt. Soc. Amer. A*, vol. 15, pp. 2059–2065, 1998.
[11] F. Okano, J. Arai, K. Mitani, and M. Okui, "Real-time integral imaging based on extremely high resolution video system," *Proc. IEEE*, vol. 94, no. 3, pp. 490–501, Mar. 2006.

[12] H. Navarro, J. C. Barreiro, G. Saavedra, M. Martínez-Corral, and B. Javidi, "High-resolution far-field integral-imaging camera by double snapshot," *Opt. Express*, vol. 20, pp. 890–895, 2012.

[13] J.-H. Park, K. Hong, and B. Lee, "Recent progress in three-dimensional information processing based on integral imaging," *Appl. Opt.*, vol. 48, pp. H77–H94, 2009.

[14] B. Javidi, R. Ponce-Díaz, and S.-H. Hong, "Three-dimensional recognition of occluded objects by using computational integral imaging," *Opt. Lett.*, vol. 31, pp. 1106–1108, 2006.

[15] B. Heigl, R. Koch, M. Pollefeys, J. Denzler, and L. Van Gool, "Plenoptic modeling and rendering from image sequences taken by hand-held camera," in *Proc. DAGM*, 1999, pp. 94–101.

[16] S. Yeom, B. Javidi, and E. Watson, "Photon counting passive 3D image sensing for automatic target recognition," *Opt. Express*, vol. 13, pp. 9310–9330, 2005.

[17] A. Stern and B. Javidi, "Three-dimensional image sensing, visualization, and processing using integral imaging," *Proc. IEEE*, vol. 94, no. 3, pp. 591–607, Mar. 2006.

[18] D.-H. Shin, H. Yoo, C.-W. Tan, B.-G. Lee, and J.-J. Lee, "Occlusion removal technique for improved recognition of partially occluded 3D objects in computational integral imaging," *Opt. Commun.*, vol. 281, pp. 4589–4597, 2008.

[19] B. Tavakoli, B. Javidi, and E. Watson, "Three dimensional visualization by photon counting computational integral imaging," *Opt. Express*, vol. 16, pp. 4426–4436, 2008.

[20] S.-H. Hong, J.-S. Jang, and B. Javidi, "Three-dimensional volumetric object reconstruction using computational integral imaging," *Opt. Express*, vol. 12, pp. 483–491, 2004.

[21] D. Shin, M. Daneshpanah, and B. Javidi, "Generalization of three-dimensional N-ocular imaging systems under fixed resource constraints," *Opt. Lett.*, vol. 37, pp. 19–21, 2012.

[22] J.-S. Jang and B. Javidi, "Improved viewing resolution of three-dimensional integral imaging by use of nonstationary micro-optics," *Opt. Lett.*, vol. 27, pp. 324–326, 2002.

[23] J.-Y. Son, S.-H. Kim, D.-S. Kim, B. Javidi, and K.-D. Kwack, "Image-forming principle of integral photography," *IEEE J. Display Technol.*, vol. 4, no. 3, pp. 324–331, Sep. 2008.

[24] J.-H. Park and K.-M. Jeong, "Frequency domain depth filtering of integral imaging," *Opt. Express*, vol. 19, pp. 18729–18741, 2011.

[25] Z. Kavehvash, M. Martinez-Corral, Kh. Mehrany, S. Bagheri, G. Saavedra, and H. Navarro, "Three-dimensional resolvability in an integral imaging system," *J. Opt. Soc. Amer. A*, vol. 29, pp. 525–530, 2012.

[26] M. H. Kalos and P. A. Whitlock, *What Is Monte Carlo?, in Monte Carlo Methods*. , Weinheim, Germany: Wiley-VCH Verlag GmbH, 2007.

[27] J. W. Goodman, *Introduction to Fourier Optics*, 2nd ed. New York: McGraw-Hill, 1996, ch. 4.

[28] M. Cho and B. Javidi, "Optimization of 3D integral imaging system parameters," *J. Display Technol.*, vol. 8, no. 6, pp. 357–360, Jun. 2012.

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