

3D capturing devices based on the principles of Integral Photography

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Abstract

In this article novel approaches for capturing 3D scenes are presented based on the technique of Integral Photography. The novelty in our method includes the development of robust, low complexity and high accuracy capturing devices using a depth control lens for managing the reconstruction of the 3D scene in front or behind the surface of the display device. To this end, high-resolution CCD sensors are used using appropriate lens arrays to perform capturing. Results obtained are presented together with an analysis and details regarding the representation layer.

Keywords: Integral Photography, Integral Imaging, Three-dimensional Image Processing, 3D Displays, 3D Imaging

1. Introduction

Integral Photography (IP) or Integral Imaging, devised by Lippmann [1] in 1908, is a very promising method for capturing and reproducing three-dimensional scenes. This technique does not require any special means for the observation of the 3D image while offers full parallax both in vertical and horizontal dimensions and reproduces colors perfectly. 3D image observation is concurrently possible by multiple observers and a long observation time does not cause any eye fatigue. The utilization of IP in 3D imaging has been lagged for many years due to the high resolution required for the capturing and reproduction devices. However, today there is a revitalizing interest in IP with the evolution in micro-optics, high resolution CCDs and LCDs together with the increased computational power of modern CPUs.

IP is based on the concurrent capture of many different views of the 3D scene by the utilization of a microlens array (MLA) in the capturing stage as depicted in Figure 1a. Each captured IP image consists of a grid of microimages in which each area of adjacent microimages depicts different views of the same part of the 3D scene.

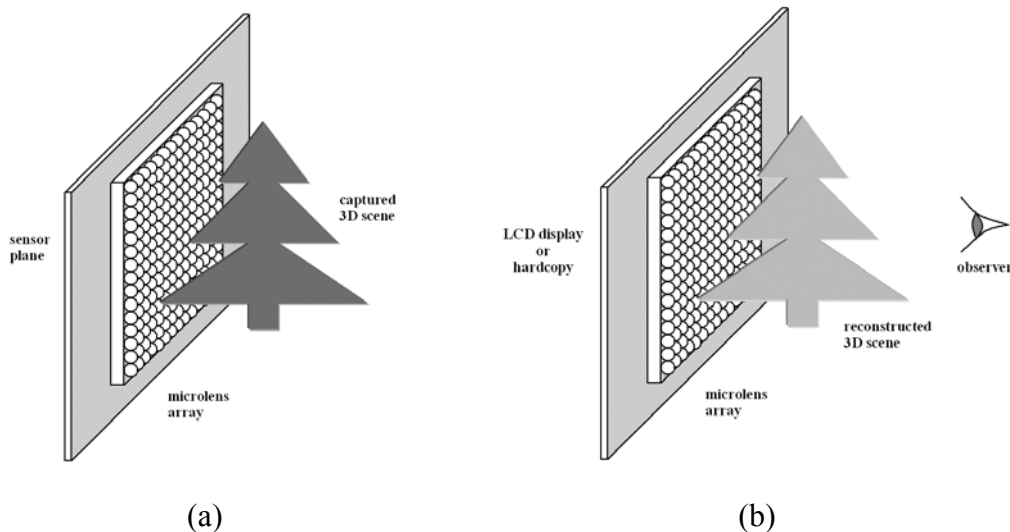


Figure 1. Integral photography capturing and reconstruction stage. (a) capturing stage (b) reconstruction stage (the 3D scene is shown in space for clarity)

On the reconstruction stage, a LCD display or a hardcopy together with an appropriate MLA can be used for the reproduction of the three-dimensional scene. The microlens array is positioned on top of the LCD panel or the hardcopy as depicted in Figure 1b and the 3D scene is formed in space. Reproduction at the same

distances as those of the capturing stage is possible if the same MLA is used both at the capturing and reproduction stage.

The produced integral images are pseudoscopic because of the inversed depth phenomenon that is inherent in a single stage IP capturing system. The production of orthoscopic IP images can be accomplished either by using Gradient Index (GRIN) lens arrays [2] or an additional set of two lens arrays placed back-to-back [3]. However, GRIN MLAs are very expensive while a two stage capturing setup causes a severe degradation of the quality of the captured image. In this work, the captured pseudoscopic images are digitally processed and converted to orthoscopic ones, by performing an 180° rotation of each microimage around its optical axis [4].

2. IP capturing setup with depth control

In a basic IP capturing setup like the one depicted in Figure 1a, the 3D scene cannot be formed at the reconstruction stage in space in front of the display panel but only behind it (exhibits depth only). A modification of a single stage IP capturing setup based on an additional imaging lens has been proposed [5] and a computer simulation [6] has produced excellent results. This modified setup allows depth control and a variation of it based on a CCD capturing device is depicted in Figure 2.

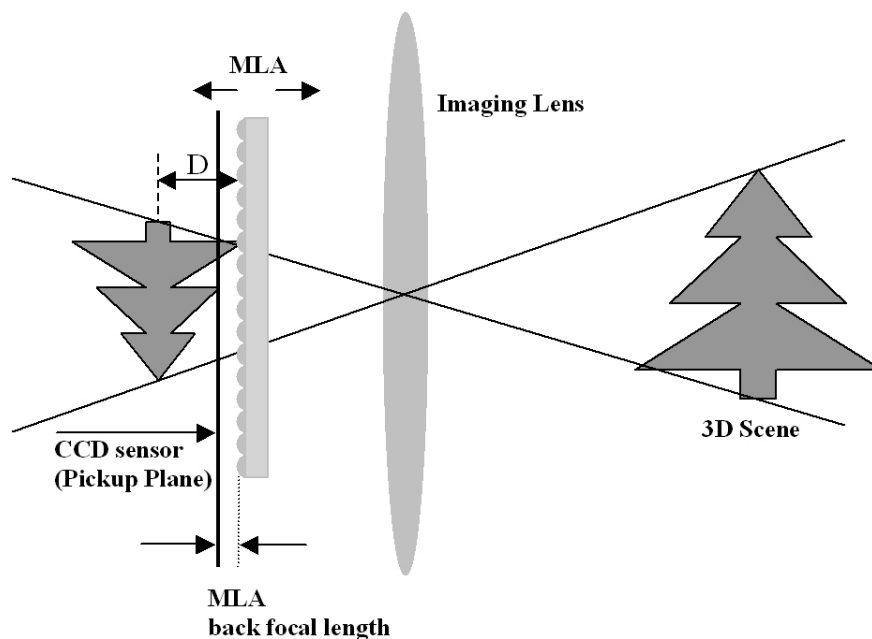


Figure 2. IP capturing setup with depth control through the use of an imaging lens. The MLA is sampling the image space at variable depths.

An imaging lens is appropriately inserted between the MLA and the 3D scene producing a real image of the scene. The MLA is positioned in the image space at variable depths. Both real and virtual IP images can be produced depending on the position of the MLA in the image space [6].

The relative distance D of the MLA in regard to the median plane of the image space, determines which parts of the IP image are real or virtual. When the MLA is positioned at the end of the image space towards the imaging lens as in Figure 2, a virtual pseudoscopic integral image is produced. This image when pseudoscopically corrected, results to a real orthoscopic integral image. At the reconstruction stage, the 3D scene floats in space in front of the MLA towards the observer. This kind of 3D reconstruction is more attractive and realistic to the observer than a virtual one [5] and for this reason it has been selected for realization in the capturing setup.

Furthermore, by placing the MLA within the image space, both real and virtual integral images are produced.

3. IP capturing setup using a flatbed scanner.

An interesting approach for using CCDs in IP image capturing setup is the utilization of a low cost flatbed scanner. A scanner of this type has been studied for the capturing of light fields [7], [8] using low cost discrete plastic lenses of one-inch pitch and $f\#$ equal to 2.5 thereby suffering from severe optical aberrations. In this work, the capturing setup is based on current technology high-resolution microlens arrays and is realized either without or with depth control.

A simple IP capturing setup using a flatbed scanner can produce high quality IP images by positioning the MLA on the scanner glass and the 3D object directly in front of the MLA. An IP image captured with this setup by a Microtek 6100 flatbed scanner with a medium format transparency adapter is depicted in Figure 3. The MLA used was a Fresnel Technologies [9] square microlens array, with 1mm pitch size and f number ($f\#$) equal to 3.3. The captured real pseudoscopic IP image was digitally processed to eliminate pseudoscopic effects and converted to virtual orthoscopic. No imaging lens was used, therefore depth control was not available and at the reconstruction stage the 3D object was formed behind the display device plane.

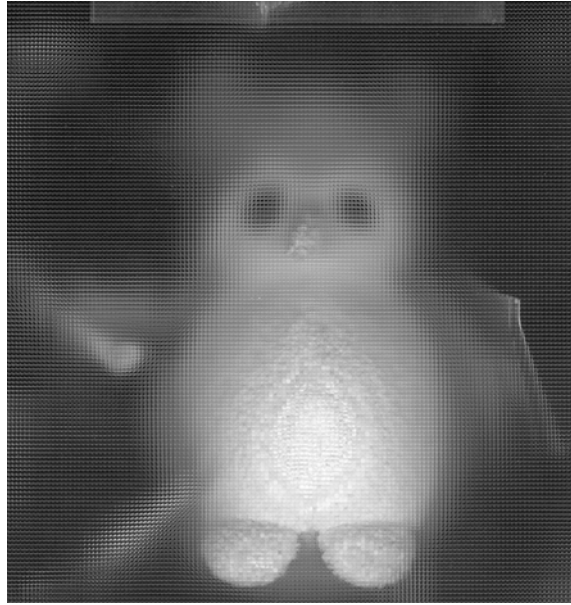


Figure 3. Capture of a real pseudoscopic IP image using a flatbed scanner. The 3D object is positioned directly in front of the capturing MLA.

However, this capturing technique presents disadvantages, such as:

- Demand for strong and appropriate lighting conditions.
- Low complexity 3D scenes with limited depth. A typical flatbed scanner has restricted ability for scanning 3D objects. Above distances in the order of 10cm the captured 3D image exhibits severe distortion across the scanning axis. Therefore, the depth of the captured 3D scene is practically limited to a few centimeters.
- Requirement for a completely motionless 3D scene during the scanning process, which can last up to several minutes depending on the required scanning resolution.
- Small sampling resolution. Inadequate quality and misalignments in the lenses and mirrors of a flatbed scanner cause a reduction in the quality of the captured IP image. Furthermore, the number of photosites on its sensor limits the optical horizontal resolution. Therefore, the actual number of pixels that carry 3D information under each microlens in the IP image is substantially restricted and a typically minimum acceptable number of 10x10 pixels can only be attained by the utilization of MLAs with large microlens pitch.

- Real orthoscopic IP images cannot be produced. These images could be used at the reconstruction stage to form a floating 3D scene at the space in front of the display device.

As a next step towards real IP capturing with depth control, an extension of this simplified setup was made by the implementation of an imaging lens. A high-quality large aperture bi-convex lens, as the one depicted in Figure 4a, could be used as an imaging lens but would cause severe distortions to the 3D image. A bi-convex lens was actually tested, however the results were inadequate for the required IP image quality. Specifically, the distortion of the 3D scene image was prohibiting for the digital process of the captured IP image and the reconstruction of the 3D scene in space. Therefore, a camera lens was utilized, specifically a Canon 135mm f/3.5 lens. This lens has a manually controlled aperture, which was opened to maximum.

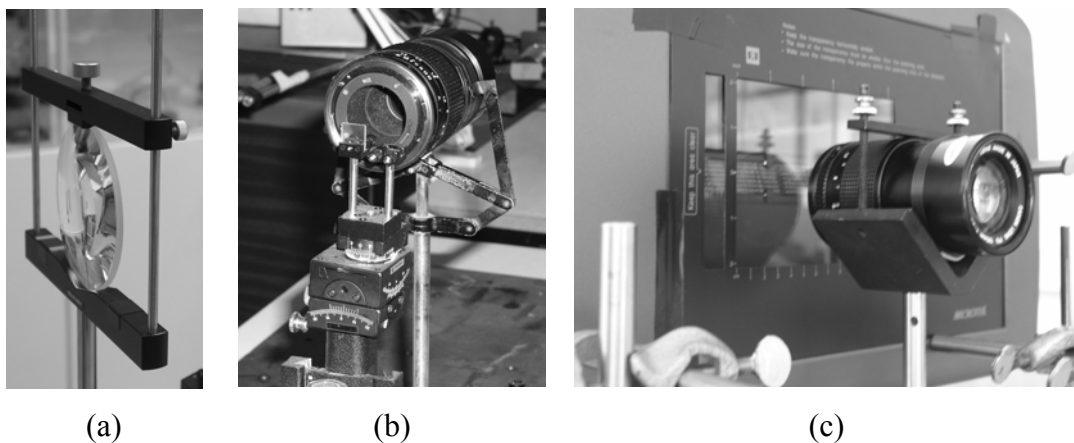


Figure 4. Integral Photography capturing setup with depth control using a flatbed scanner (a) high quality bi-convex lens tested as imaging lens (b) micro-positioning of a high resolution MLA in the image space of a Canon lens (c) IP capturing setup using a flatbed scanner and a Canon lens (the MLA is positioned on top of the scanner glass).

The minimum focusing distance of this Canon lens is 1.3m and the focused image of the 3D scene is formed at 3.5cm behind the back end of the lens (at the film plane). A scanned image of a 3D screen is depicted in Figure 5a. For IP capturing, the MLA is positioned on top of the scanner glass with the microlenses towards the imaging lens at a distance of 3.5cm from the back end of the lens. Depth control is available

through the focusing knob of the lens since a defocused lens image corresponds to increased depth in the IP capturing setup.

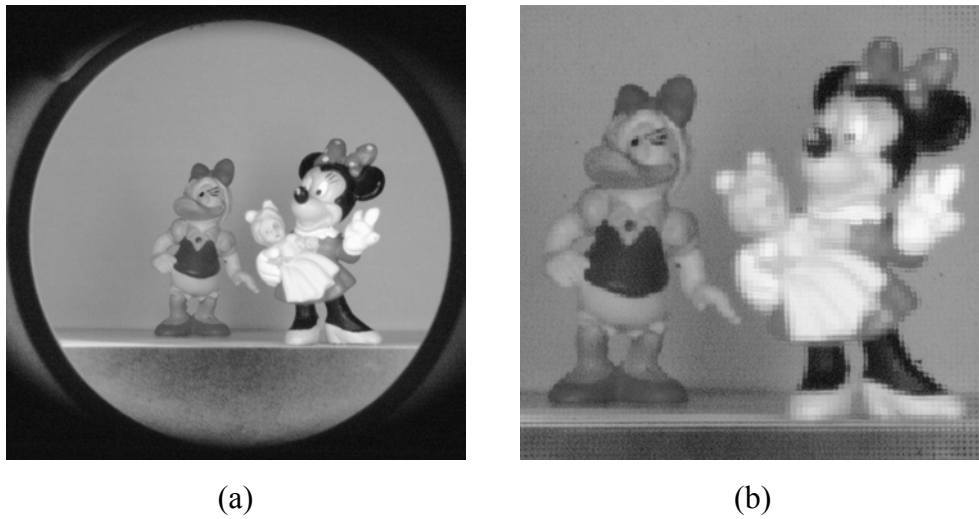


Figure 5. Single stage IP captured images. (a) 3D scene image captured by the scanner (no MLA used) (b) IP image captured by the scanner (the back doll is in focus while the front doll is out of focus exhibiting depth in the IP captured image).

With this IP capturing setup, a 3D scene with adequate lateral and longitudinal dimensions can be captured, as depicted in Figure 6.

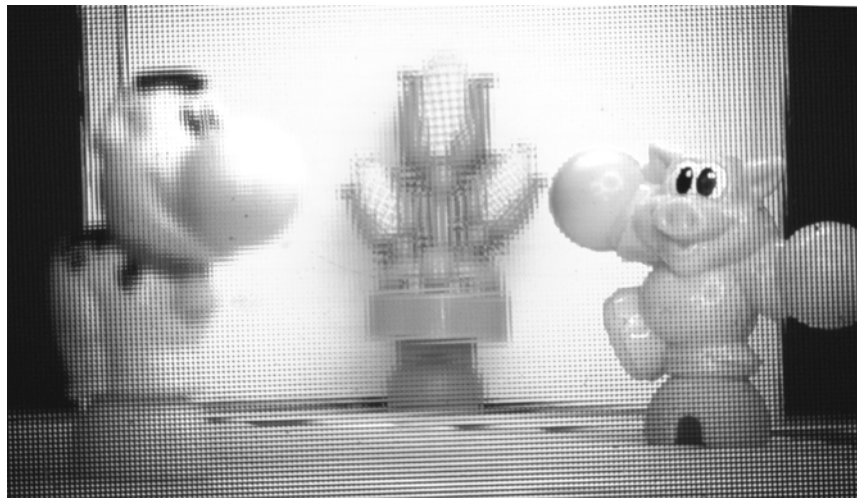


Figure 6. Capture of an IP image with both real and virtual parts using a flatbed scanner. The 3D scene is formed by three different dolls, which are positioned at different depths. An imaging lens has been used in the capturing stage therefore depth control is available. The doll to the right is in focus while the other two are in front and behind the median image plane respectively. At the reconstruction stage, the doll to the right is formed at the display panel, the left doll is formed in space in front of the display panel and the back doll is formed behind the display panel.

The disadvantage of this setup is that since we have utilized a 35mm camera lens, the lateral image size is limited to a 24x36 mm frame. Therefore the sampling MLA should have a pitch size small enough to ensure adequate sampling resolution while concurrently provide a large number of microlenses in the 24x36 mm capturing frame. To demonstrate the significance of the sampling resolution, two MLAs produced by Fresnel Technologies [9] with substantially different pitch sizes (ratio 8/1) are depicted in Figure 7.

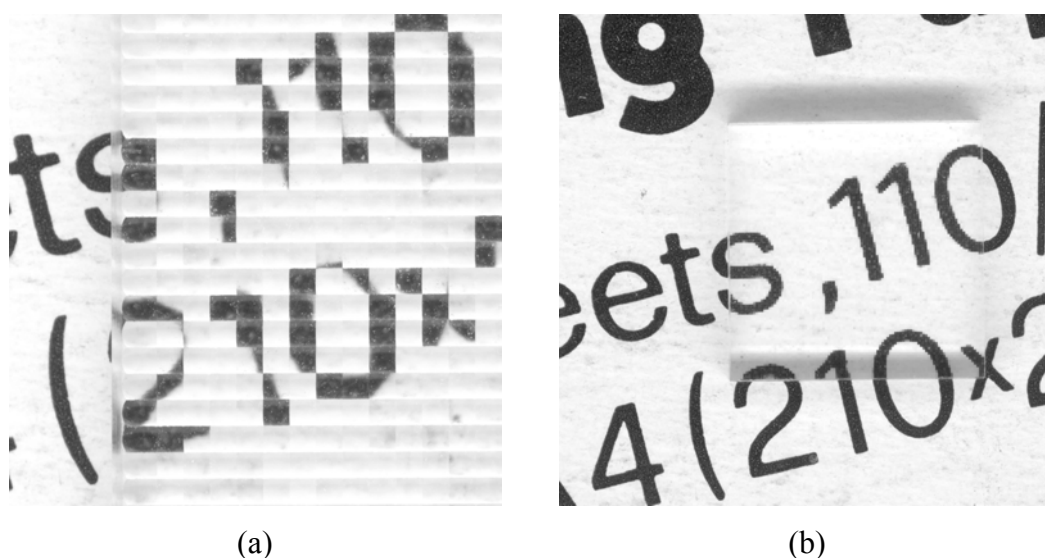


Figure 7. Square MLAs of Fresnel Technologies. (a) square MLA with 1mm microlens pitch and $f\# = 3.3$ (b) square MLA with 125 μm microlens pitch and $f\# = 19.2$ (to depict the pitch size more clearly, behind the MLAs a printed text document has been inserted)

To achieve a number of 10x10 pixels under each microlens with 125 μm pitch size, scanning resolution should be at least equal to 2032dpi. Low cost flatbed scanners claim to have resolutions at least 2400dpi. However the resolving power of low cost flatbed scanners is not adequate to the task of accurate high-resolution scanning and consequently the number of pixels under each microlens of the IP image that carry actual 3D information is not enough. A film scanner, which offers much higher actual scanning resolution and a higher resolving power, would be more appropriate to scan the IP image but the cost is much higher than that of a flatbed scanner. Alternatively, Contact Image Sensor (CIS) scanners could be used which have no optical elements and mirrors and therefore would offer in the near future the actual necessary scanning resolutions for IP capturing.

4. IP capturing setup using a digital camera

Research has been made on IP capturing of 3D scenes using a compact digital camera [10]. In this work, the MLA was attached externally in front of the camera lens but the outputs were very poor.

The most important recent work regarding 3D capturing has been presented in [11] and uses a camera with a digital back. This work is based on light fields [7] and uses an MLA to capture 3D scenes. The 3D information is processed through the frequency domain and the results refer to focusing at different depths of the 3D scene. However, there is no reference to the different views of the 3D scene and most important to the reproduction of the 3D scene in space.

The replacement of the scanner by an actual high resolution CCD sensor fulfills the increased demand in scanning resolution. The resulting setup matches that of a digital camera. The IP image quality depends on the resolution of the CCD sensor and the optics of the MLA. The $f\#$ of the camera lens and the MLA should be matched [11]. Furthermore, small microlens pitch sizes, combined with increased $f\#$, result to microlenses with small curvatures and consequently reduced aberrations. Furthermore, an IP capturing setup based on a digital camera makes possible the capturing of moving objects and offers great flexibility in lighting conditions.

However, a setup based on a digital camera cannot be easily accomplished since small format digital cameras are usually compact. Therefore, a microlens array cannot be easily inserted in front of the CCD sensor especially with the required micro-positioning control. This is clearly depicted in Figure 8, in which we trace rays incident at the substrate side of an MLA. The exiting rays converge to the focal plane

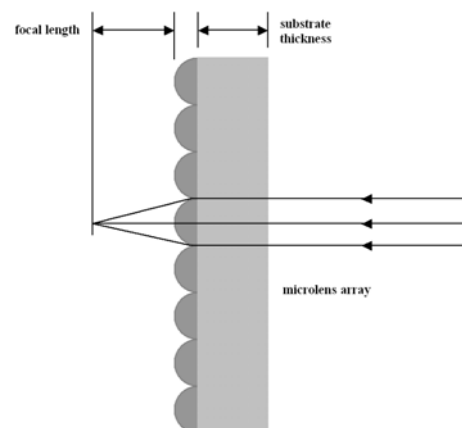


Figure 8. Convergence of rays coincident on an MLA from the substrate side.

of the MLA. At this plane the CCD sensor should be positioned for capturing of a focused IP image.

Therefore, a professional medium format photographic camera was utilized which could be easily disassembled in parts and accepted either film or a digital back with a high-resolution CCD sensor.

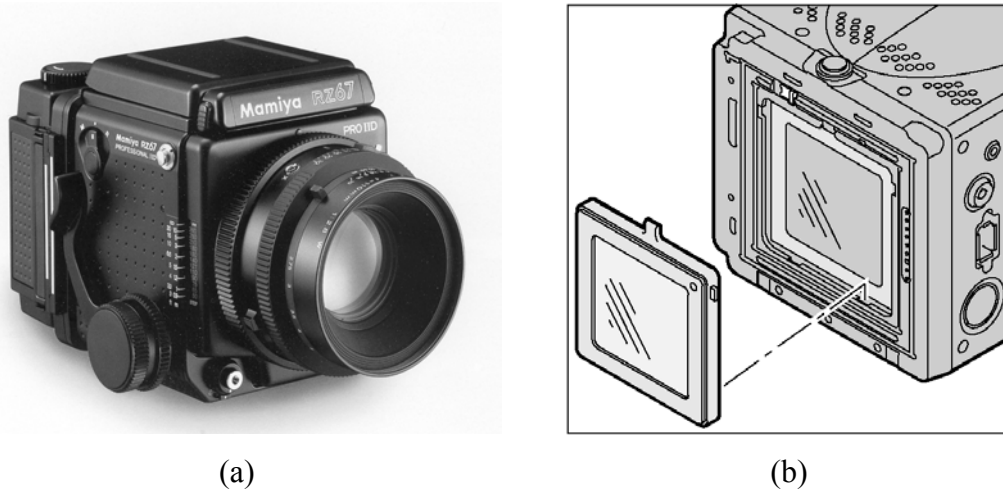


Figure 9. (a) Professional medium format camera Mamiya RZ Pro IID, accepting either film or a digital back. (b) Digital back Kodak DCS Pro Back Plus (the CCD sensor and a removable IR filter are depicted in the Figure).

The digital back Kodak DCS Pro Back Plus is equipped with the Kodak full frame color CCD sensor KAF 16802CE with dimensions 3.7cm x 3.7cm and pixel size 9 μ m. This sensor has 4080x4080 active pixels (16Mpixels) offering the required high resolution for IP capturing. When an MLA with pitch size 125 μ m is placed in front of this sensor, we get 13x13 pixels under each microlens. Depending on the f# of the MLA used, the captured IP image exhibits depth information or both depth and multiview 3D content.

5. Conclusions and future work

The rapid improvement in CCD sensors (with current values of 50Mpixels) as well as in the manufacturing technology of micro-optics will result in the near future in three dimensional capturing setup of very high resolutions, using MLAs with

microlens pitch in the order of $100\mu\text{m}$. These 3D capturing systems will provide several tens of pixels under each microlens dimension.

However, the resolution of the LCD displays increases slowly and current resolutions are in the order of 200dpi with minimum dot pitch 0.1mm. Therefore, LCD displays match at the present time with MLAs of at least 1mm pitch which would give 10×10 pixels under each microlens, which is the typical requirement for acceptable quality of Integral Photography images.

The reproduction of a 3D scene based on a high resolution IP captured image is not therefore straightforward, requiring digital processing to scale the captured IP image to the geometrical and optical parameters of the MLA used at the reproduction stage [12]. This scaling primarily depends on the pitch ratio of the capturing and reproduction MLAs as well as on their focal length ratio. Generally, there will be a loss in 3D information during scaling from one MLA to another.

Moreover, the 3D information content of a captured IP image can be revealed indirectly by downsampling the IP image by appropriate spatial filtering of the pixel information under each microimage. The downsampled images are 2D projections of the 3D scene and directly reveal information about the different views of the 3D scene as well as the scene depth by focusing at different depths. Outputs from the application of such algorithms on synthetic IP data are depicted in [13].

Work has to be done in the field of digital cameras for the development of the next generation 3D cameras that incorporate 3D capturing systems as well as the required processing algorithms.

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