Real-Time All-Optical Three-Dimensional Image Projector

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Abstract

We propose the use of synchronously moving micro-optics (lenslet arrays) for image pickup and display in three-dimensional integral imaging to overcome the upper resolution limit imposed by the Nyquist sampling theorem. With the proposed technique, we present an all-optical three-dimensional integral imaging projector. An optically addressed spatial light modulator is used, which potentially provides better image resolution than the conventional CCD and liquid crystal display pair. We present experimental results using a liquid crystal light valve.

1. Introduction

Integral imaging (II) is a method to obtain a three-dimensional (3-D) image by use of a set of two-dimensional (2-D) elemental images with different perspectives. It was first proposed by Lippmann in 1908 and is actively studied currently for 3-D TV and visualization.[1-5] Figure 1 shows a conventional II. The multiple elemental images that have different perspectives for a given 3-D object are usually generated by micro-optics array of lenslets, and then they are recorded in a 2-D light sensitive device such as a charge-coupled device (CCD). A 3-D image of the object is reconstructed by displaying the recorded 2-D elemental images in front of another lenslet array. Thus it is possible to detect, transmit, and manipulate 3-D images in their 2-D forms.

There are two important factors that deteriorate the viewing resolution of reconstructed 3-D images, in addition to aberration and mis-alignment of micro-optics. One factor is the pitch of the lenslets, which determines the spatial sampling rate in image pickup and display.[6] One cannot reduce the pitch of the lenslets (and consequently the lenslet size) arbitrary, because diffraction also limits the viewing resolution.[3] Recently we developed a non-stationary lenslet array technique to overcome the viewing resolution limit imposed by the Nyquist sampling theorem for a given lenslet pitch.[7] The other factor is the resolution of the image pickup and display devices.[8,9] This is because the 2-D elemental images, which are the components of the 3-D image to be reconstructed, should have sufficient resolution.

In this paper, we propose an all-optical 3-D II projector. We use an optically addressed spatial light modulator (SLM) [liquid crystal light valve (LCLV)] as an image pickup and display device. The optically addressed SLM can potentially provide higher image resolution than commercially available liquid crystal displays do.[10] The LCLV has about 20 lines/mm over approximately 5 cm ×5 cm area. In addition, the use of the LCLV makes all-optical parallel pickup and display possible, in which converting optical signals to video signals and vice versa is not necessary. We also demonstrate that a non-stationary lenslet array technique can be applied to our system to reconstruct 3-D images with improved viewing resolution.

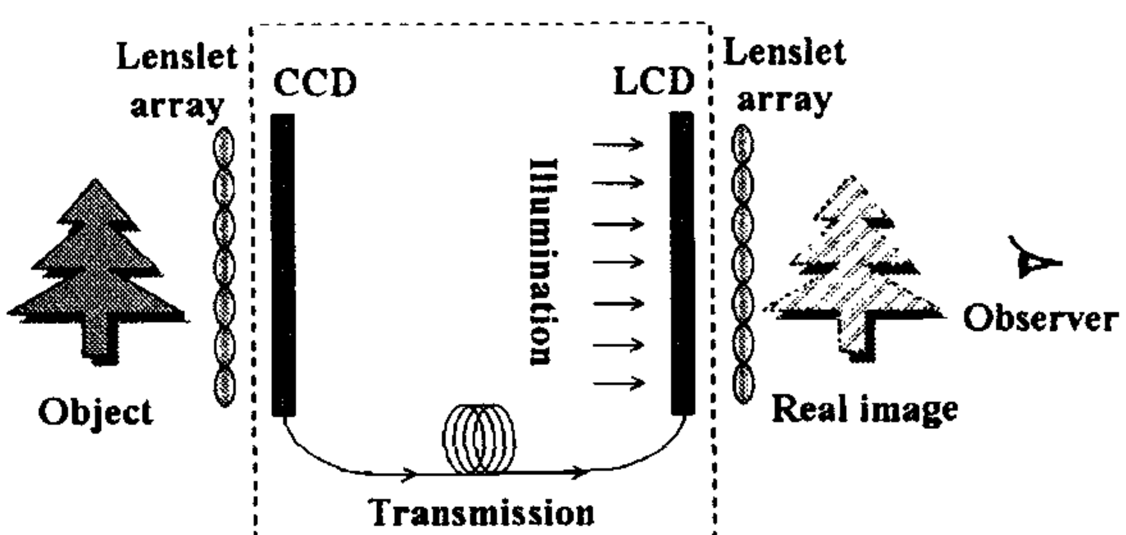


Fig. 1. Direct pickup and display for integral imaging.

2. Experimental system description

Figure 2 presents our 3-D integral imaging projector. The detector and display devices depicted in the dashed box of Fig. 1 is replaced with the LCLV.[13] The LCLV is a compact optical-to-optical image transducer that is capable of accepting a low intensity input light image and converting it, in real time, into an output image with light from another source. It is basically composed of a thin (2-3 μm) liquid crystal layer (the read-out surface) and a photosensor layer (the writing surface). Between the two layers there are a dielectric mirror to reflect the read-out beam and a light-blocking layer to isolate the input and output images optically. Through two transparent conductive electrodes, an AC voltage (5-10 volt rms) in the range of audio frequency is applied to the whole sandwich of layers. Because the conductivity of the photosensor layer in the writing surface changes spatially according to the intensity distribution of the input image, the AC electric field intensity at the thin liquid crystal layer also changes spatially. Hence, the optical birefringence of the thin film liquid crystal layer can be modulated by the input image in the writing surface. When a polarized uniform beam is incident on the read-out surface, the polarization state of the reflected beam from the dielectric mirror changes spatially because of the modulated birefringence of the liquid crystal layer. By passing the reflected read-out beam through a polarizer (called an analyzer), an amplified output image with high contrast (larger than 100:1) and high resolution (because it is not a pixel-based device) can be obtained in general.[10]

As depicted in Fig. 2, the pickup lenslet array denoted by LA1 generates multiple 2-D elemental images of an object. These elemental images are transmitted, through relay optics such as fiber bundle, to the writing surface of the LCLV. The written elemental images are read out with a polarizing beam splitter (PBS), an analyzer (P1), and a polarized incoherent beam that is obtained by passing incoherent light through another polarizer (P2). The read-out elemental images can be transferred through additional relay optics to the display lenslet array (LA2). Finally, the reconstructed 3-D image is captured by a CCD camera, and is also examined with our naked eyes.

The real image reconstructed by LA2 is pseudoscopic. A simple solution to reconstruct the orthoscopic image is to invert every elemental image at their own center of optic axis.[11] To achieve this, an

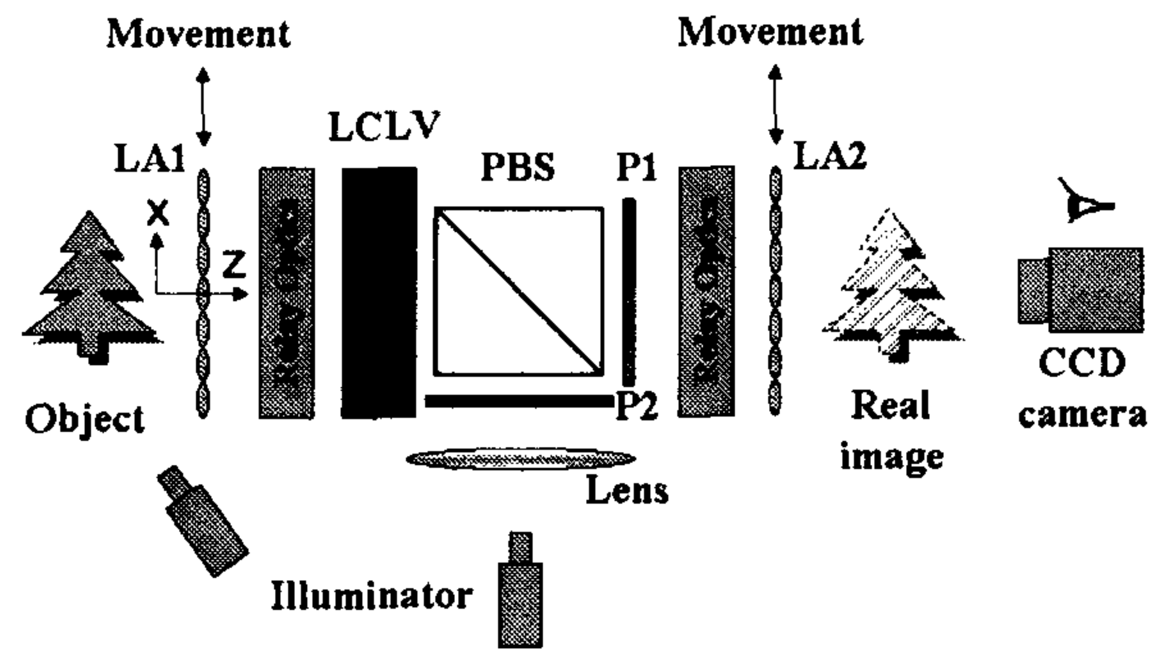


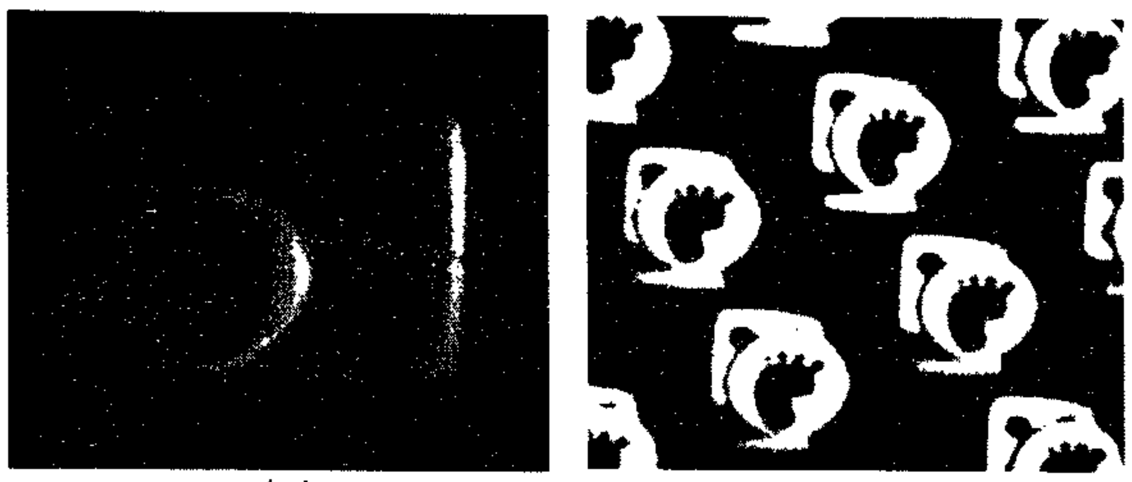
Fig. 2. All-optical 3-D integral imaging projector.

array of graded-index rod lenses with a proper rod length can be used instead of either LA1 or LA2 in our system, as Arai et al. have proposed.[11] Here, we used conventional lenslet arrays for simplicity.

3. Experiments

The object used for 3-D imaging is composed of a die and a plastic button with a footprint figure as shown in Fig. 3(a). The side length of the die is 1.5 cm and the diameter of the button is 1 cm. The distance between the button surface with the footprint figure and the die surface with four dots is about 3 cm. The lenslet arrays we used have 53x53 lenslets. Each lenslet element is square-shaped and has a uniform base size of 1.09 mm × 1.09 mm, with less than 7.6 μm separating the lenslet elements. The focal length of the lenslets is 5.2 mm. LA1 and LA2 are both tilted around the optic axis (*z* axis) by an angle of about 30° from the horizontal direction of the objects (*x* axis). The lenslets are mounted on translation stages, and can be moved together simultaneously. The distance between LA1 and the surface of the button is approximately 4 cm. We used the LCLV developed by Hughes Research Laboratories (Model H-4060). The diameter of the LCLV aperture is 50 mm. For simplicity, we used a camera lens whose focal length is 50 mm and *f* number is 1.4 as the relay optics. The CCD camera that is used to capture the reconstructed output image has a standard camera lens with a built-in iris. The focal length and the maximal *f* number of this camera lens are 50 mm and 1.2, respectively.

The size of each elemental image exposed to the writing surface is approximately 2 mm. The diameter of the smallest toe image is approximately 80 μm in this case. A few read-out elemental images from the



(a) (b)

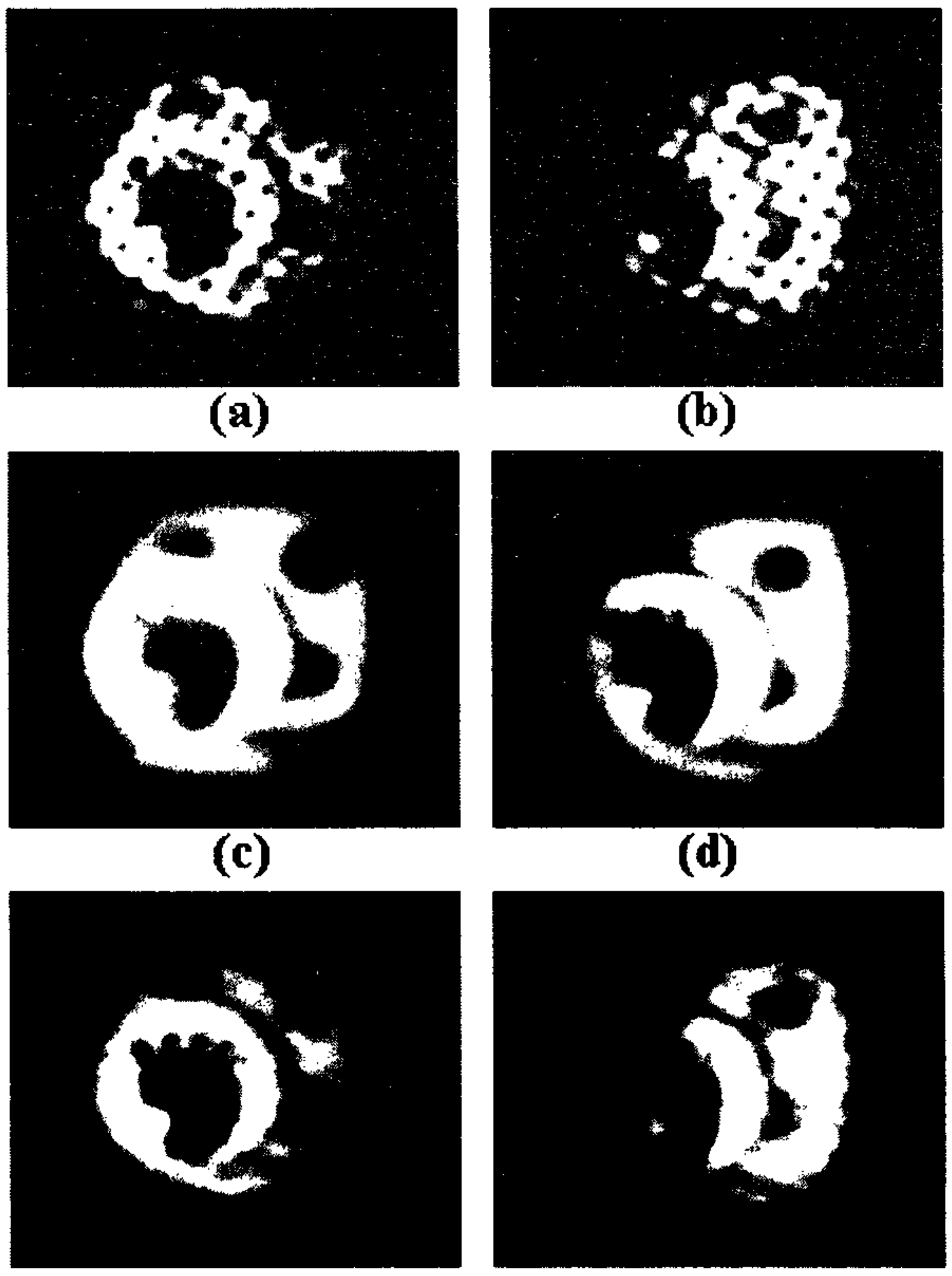
Fig. 3. (a) 3-D objects used in the experiments. (b) Elemental images read-out from the LCLV.

LCLV are shown in Fig. 3(b). We can see that the LCLV has enough resolution to represent the toe images clearly. When we view the reconstructed real image with our naked eyes, we can visualize the 3-D nature of the image, although it is pseudoscopic. The die surface looks closer to us than the footprint figure does.

The reconstructed 3-D image captured by the camera is shown in Fig. 4(a). Here, the pupil diameter of the camera lens is approximately 10 mm or less. Note that the pupil diameter of the human eye is about 3 mm in an ordinary environment. Thus, when we observe the reconstructed images, the toes in the footprint figure are not clear, although the dots in the die are clear. This is because the toes are similar to or smaller than the lenslet pitch. To show that the reconstructed image has the 3-D nature, we changed the position (and accordingly the viewing angle) of the CCD camera and captured the reconstructed 3-D image again. This image is shown in Fig. 4(b). The reconstructed images in Fig. 4(a) and 4(b) indicate that even if the resolution of both the pickup and display device is high enough, the image is poor quality because of the array structure of lenslets.

The resolution of the reconstructed image captured by the CCD camera is dependent on the pupil size of the CCD camera lens.[7] For a given lenslet array pitch, it is possible to capture a reconstructed image of improved resolution if the pupil diameter of the CCD camera is increased. For comparison, Fig. 4(c) and 4(d) illustrate the captured images when the iris of the CCD camera is opened maximally. In this case, the toe images become clear. Unfortunately, the pupil diameter of our eyes is small, so we cannot observe the images with equal resolution.

To improve our viewing resolution, we adopt a non-stationary micro-optics (lenslet array) technique.[11]



(a) (b) (c) (d) (e) (f)

Fig. 4. Experimental results for 3-D image reconstruction. (a), (c), and (e) are the images captured when the CCD camera is on the optical axis. (b), (d), and (f) are 3-D images captured when the camera is off the axis. (a) and (b) 3-D images when the iris pupil diameter of the CCD camera lens was reduced to 10 mm. (c) and (d) 3-D images when the iris was maximally opened. In this case, its pupil diameter was about 42 mm. (e) and (f) 3-D images when the CCD pupil diameter was reduced to 10 mm and lenslet arrays are set in motion.

In this technique, the positions of the lenslet arrays for both pickup and display are rapidly changed synchronously in the lateral directions. This motion generates moving elemental images of many different perspectives within the time constant of our eyes response time. Although the elemental images move, the reconstructed 3-D image does not move because the display lenslet array also moves synchronously. Because our eyes have a limited time constant and the spatial sampling rate by the lenslets is effectively increased, we only see a stationary reconstructed image with improved resolution for a stationary object. The price we have to pay for the improved viewing resolution in the non-stationary lenslet array technique is that we have to use the image pickup and display devices that are fast enough to represent non-stationary elemental images.

When the lenslets are packed in a square lattice, 2-D motions are necessary to increase the spatial sampling rate along mutually orthogonal two lattice directions in general. Because the lenslet arrays have a periodic structure, however, even if the lenslet arrays move only along the x axis, we can increase the sampling rate along the two lattice directions (x' and y' directions) if we tilt (in-plane rotation) the lenslet arrays around the z axis by θ, where θ is the angle between x and x'. Because the surfaces of the lenslet arrays remain normal to the z axis, astigmatism is not introduced.

The temporal response time of the LCLV used in our experiment is approximately 100 ms. Thus we cannot directly apply the non-stationary lenslet array technique because the temporal response time of our eyes is less than 100 ms. To illustrate the effect of the non-stationary lenslet array technique in the 3-D imaging projector, we used an indirect method. First we reduced the pupil diameter of the camera lens as used when the images in Fig. 4(a) and 4(b) were obtained. Then, we captured a sequence of 34 reconstructed images by simultaneously setting in motion both lenslet arrays (LA1 and LA2) horizontally and with 50 μm steps. The movement range of the lenslet arrays does not need to be large: The range of one lenslet pitch in each direction will be enough in principle, because the lenslets are periodic. Because both lenslet arrays are already tilted by an angle of 30° around the z axis, shifting the lenslet arrays in the horizontal (x) direction increases the spatial sampling rates in both x' and y' directions. Finally, the 34 images are averaged in a personal computer to mimic the time averaging effect of our eyes. The resulting images for the on-axis and off-axis camera positions are given in Fig. 4(e) and 4(f), respectively. Although our non-stationary lenslet array technique is applied in an indirect and discrete manner, a noticeable improvement is evident because the toe images have become clear.

It is possible in principle to reduce the response time of the LCLV by increasing the writing beam intensity.[10] In addition, optically addressed SLM's such as ferroelectric devices with faster response time are available. If a fast SLM is used, the non-stationary lenslet array technique can be applied in a continuous manner, and thus direct observation of the reconstructed 3-D image with improved resolution will be possible.

4. Summary

In this paper, we have demonstrated a novel real-time all-optical 3-D II projector that provides improved viewing resolution. The viewing resolution limit imposed by the lenslet pitch can be overcome by adopting the non-stationary lenslet array technique. It is straightforward to extend our system to a 3-D II color projector by forming red, green and blue images separately either in time domain or in spatial domain and then combining them.

5. References

[1] G. Lippmann, C. R. Acad. Sci. **146,** 446 (1908).

[2] H. E. Ives, J. Opt. Soc. Am. **21,** 171 (1931).

[3] C. B. Burckhardt, J. Opt. Soc. Am. **58,** 71 (1968).

[4] T. Okoshi, Appl. Opt. **10,** 2284 (1971).

[5] Javidi and F. Okano eds, Three-Dimensional Television, Video, and Display Technology (Springer Verlag, Berlin, 2002).

[6] H. Hoshino, F. Okano, H. Isono, and I. Yuyama, J. Opt. Soc. Am. A **15,** 2059 (1998).

[7] J.-S. Jang and B. Javidi, Opt. Lett. **27,** 324 (2002).

[8] F. Okano, H. Hoshino, J. Arai, and I. Yuma, Appl. Opt. **36,** 1598 (1997).

[9] J.-S.. Jang and B. Javidi, to appear in Aug. 10th, 2002 issue of Appl. Opt.

[10] W. P. Bleha, L. T. Lipton, E. Wiener-Avnear, J. Grinberg, P. G. Reif, D. Casasent, H. B. Brown, and B. V. Markevitch, Opt. Eng. **17,** 371 (1978).

[11] J. Arai, F. Okano, H. Hoshino, and I. Yuma, Appl. Opt. **37,** 2034 (1998).