# Three-dimensional integral imaging using an elastic PDMS lens array

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## Abstract
*In this paper, we propose a three-dimensional (3D) integral imaging system using an elastic lens array instead of conventional rigid lens array. The lens array is made of polydimethylsiloxane (PDMS) that is optically transparent and flexible material. We can stretch the PDMS lens array to be expanded into a certain extent, and control the lens pitch of the system easily. That flexible design enables a fine 3D integral imaging display.*

## 1. Introduction

Integral imaging (integral photography) is one of the promising 3D display techniques. It was first proposed by Lippmann 100 years ago in 1908 [1]. Recently, it attracts much attention as an autostereoscopic 3D display for its many advantages. It has continuous viewpoints within the viewing angle and provides full-parallax. It can provide real-time full color 3D images owing to the advancement of electronic devices nowadays [2-4].

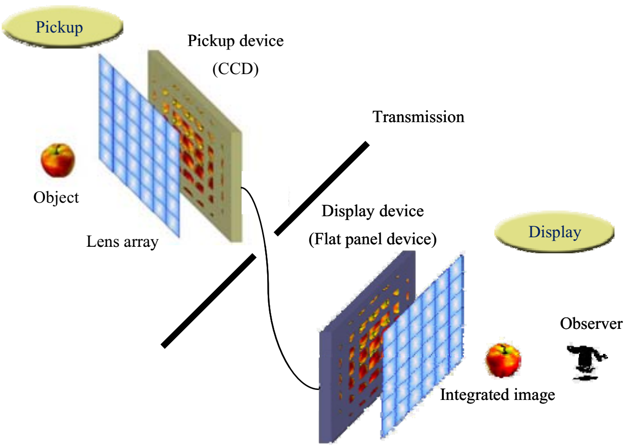


**Fig. 1. Basic concept of integral imaging**

Figure 1 shows the basic concept of integral imaging. Integral imaging 3D display is composed of two steps, pick-up and display. In pick-up step, lights from an object go through each lens in a lens array and the images are captured by pick-up device as a form of 2D image array, called elemental image. In display step, the recorded elemental image is displayed in display panel. The light rays retrace the original routes through the lens array and form a 3D image.

Here, the lens array plays an important role for 3D display. Each lens in lens array samples the corresponding pixel in its elemental image that is displayed on the display panel. It provides corresponding perspective images according to the different observation directions.

In the process of the sampling it is desirable that the lens pitch is integer times of the pixel pitch of elemental image. The lens pitch should be a multiple of pixel pitch of the display panel to provide fine perspective exactly.

However, there are various kinds of display devices with various sizes, which have a multiplicity of pixel pitch, while the type of lens array pitch is limited. It costs a lot to manufacture the lens array with specified pitch for providing exact perspective. Thus it is almost impossible to set the lens pitch as the integer times of the pixel pitch. It has been technically impossible to control the size of the lens pitch.

To solve this problem, a method using a PDMS lens array is proposed in this paper. To the authors' knowledge, this is the first proposal and experimental test of 3D display using an elastic PDMS lens array. The principle of the proposed method will be explained and the experimental results are shown.

## 2. Principle of the proposed method

We propose a method using a PDMS lens array instead of the conventional rigid lens array. PDMS is the most widely used silicon-based organic polymer [5], and is particularly known for its unusually rheological properties. Its application ranges from contact lenses and medical devices to elastomers, in shampoo, caulking, lubricating oils and heat resistant tiles. PDMS is optically clear, and is generally considered to be inert, non-toxic and non-flammable. In addition, it has a unique flexibility. We use the PDMS material to make lens array by using replica molding method.

It is one of the hyperelastic materials, which are ideally elastic materials for which the stress-strain relationship derives from a strain energy density function. This hyperelasticity is often observed in polymers. Cross-linked polymers will act in this way because initially the polymer chains can move relative to each other when a stress is applied. However, at a certain point the polymer chains will be stretched to the maximum point that the covalent cross links will allow, and this will cause a dramatic increase in the elastic modulus of the material. While a linear elastic material has a linear relationship between applied stress and strain, a hyperelastic material will initially be linear, but at a certain point, the stress-strain curve will plateau due to the release of energy as heat while straining the material.

These characteristics of flexibility and elasticity enable the PDMS lens array to be stretched into a certain extent within the linear region. It is possible to control and set the lens pitch as the integer times of the pixel pitch in display device without difficulty.

As mentioned in the above section, the lens pitch is usually not the integer times of the pixel pitch in conventional case that uses rigid lens array. The system provides uneven views. Figure 2(a) shows this situation in detail. The geometry of views can be expected easily on the assumption of ray optics. Each pixel provides corresponding view through lens. The views from lenses are integrated and corresponding perspectives are provided according to the directions. In conventional case, the number of views that each lens provides are not equal. The directions of the views that each lens provides are all different also and the viewing angle is not uniform. These decrease the viewing angle and degrade the quality of the 3D images of the system.

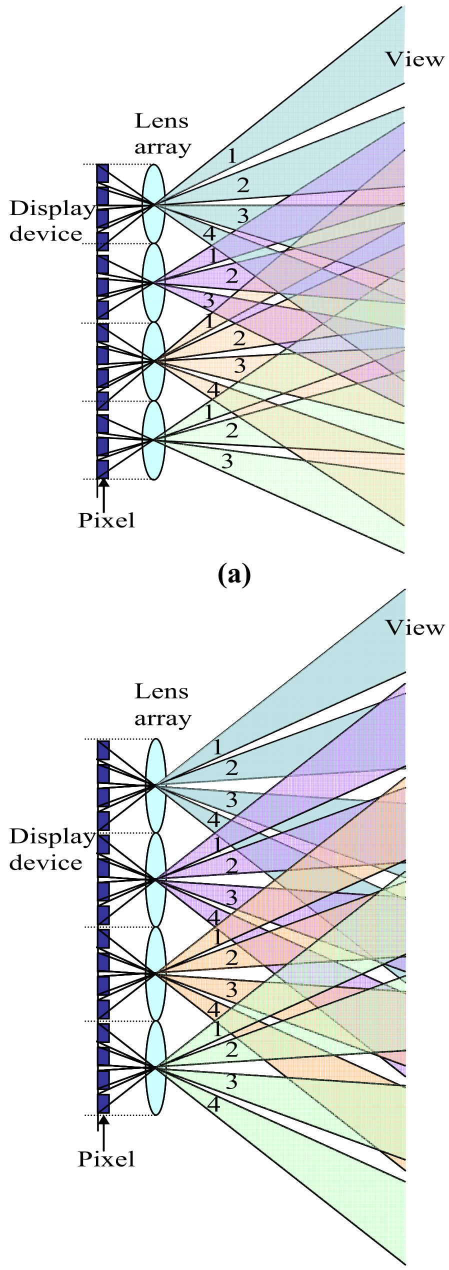


**Fig. 2. Geometry of provided views using (a) conventional method and (b) proposed method**

However, in the proposed method using elastic PDMS lens array, the lens array can be stretched to be the multiple of the pixel pitch as shown in Fig. 2(b). Each lens provides the same number of views (four views). The geometry of the views from each lens is symmetric. The directions of each view are parallel also. For example, the views numbered 1 are parallel to each other views numbered 1 regardless of the lens. The perspectives can be distributed regularly. The views numbered 1 are integrated well and fine perspective according to view 1 is provided in the direction of view 1. Similarly, corresponding fine perspectives are distributed and shown in the directions of views 2, 3 and 4. In this case the viewing angle of each lens is equal. The characteristics enable fine 3D display with exact perspectives.

The matching between the lens pitch and the pixel pitch is important when the pitch of the lens array is small compared with the pixel pitch of display.

## 3. Experimental results and discussion

The lens array is made by using replica molding method. The characteristics of the lens array, the lens pitch and the focal length, are similar with the original lens. However, it is flexible and elastic and it can be expanded easily. It is a new type of lens array. Figure 3 shows the manufactured PDMS lens array.

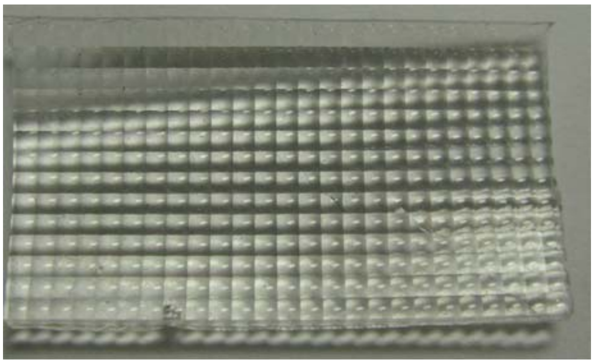

**Fig. 3. Manufactured PDMS lens array**

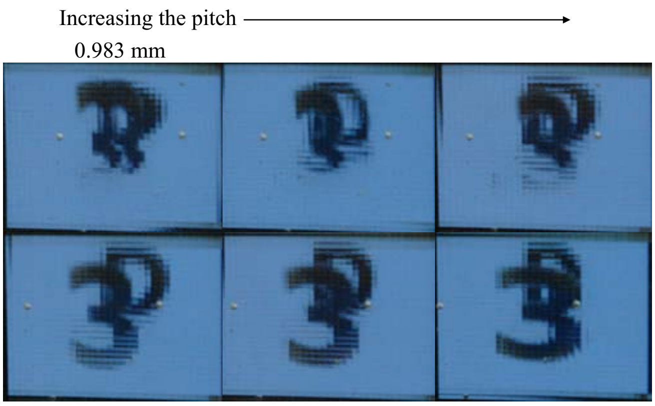


**Fig. 4. Observed images by increasing the PDMS lens pitch**

A spatial light modulator (SLM) is used as display device in this experiment. The pixel pitch is 0.036 mm and the size of the SLM is 1.8 inch. The lens pitch of original rigid lens array used for molding is about 0.983 mm. The PDMS lens array with the same pitch is manufactured. We stretched the elastic lens to have the pitch of 1.080 mm in lateral direction, which is 30 times of the pixel pitch of the SLM used in this experiment. Both sides of the elastic lens array are held tightly and the distance between the grasps are controlled by using linear stage.

The elemental image for horizontal pitch 1.080 mm is calculated and displayed in the SLM. If conventional lens array is used, the elemental images are not integrated correctly because of the difference in the lens pitch. However, if the lens array can be expanded to the exact size of the horizontal pitch, the elemental image is integrated well.

For verifying the expansion of the lens array experimental results are shown by increasing the lens pitch of PDMS lens array in Fig 4. Since the elemental images are calculated for pitch 1.080 mm, the elemental images are not integrated correctly when the lens is not stretched and 0.983 mm. As increasing the distance between the grasps, the images are integrated and better 3D images are shown. Lower center image shows integrated image with correctly stretched lens array. We can see that the lens array is expanded well.

Figure 5 shows the integrated 3D image observed from up, down, left and right directions. The different perspective of two images, 3 and D are observed. We can see that the PDMS lens array is expanded successfully in horizontal direction and the 3D images are integrated well.

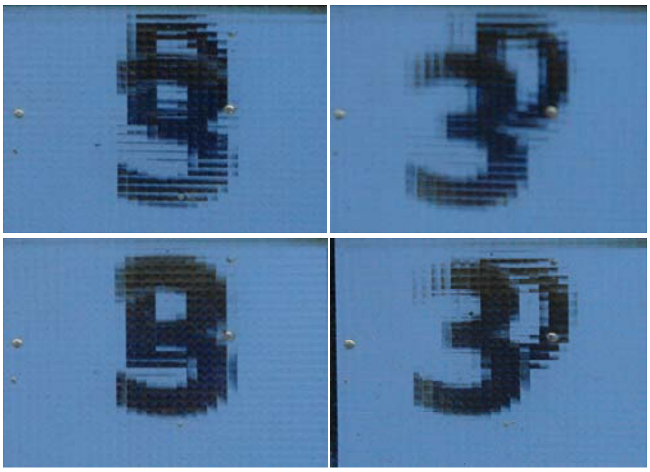

**Fig. 5. Integrated 3D images by using PDMS lens array observed from different directions (up, down, left and right).**

As the experimental results show, the PDMS lens array is expanded by about 10% in horizontal direction. There is flexibility in the size of the lens pitch. By stretching the elastic lens array we can make lens array with specified lens pitch easily.

## 4. Conclusion

This is the first proposal and experimental test of 3D display using an elastic PDMS lens array. By using the proposed method, we can make several types of PDMS lens array, which have the same geometries of the conventional lens array with replica molding method. The difference between the pitch of lens array and a multiple of the pixel pitch in display device can be overcome by stretching the elastic lens array. The proposed flexible lens enables fine 3D integral imaging system.

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