Augmented Reality 3D Displays With Micro Integral Imaging

Jingang Wang, Xiao Xiao, Hong Hua, *Member, IEEE*, and Bahram Javidi, *Fellow, IEEE*

***Abstract*—In this paper, we present a 3D augmented reality micro integral imaging display system by combining conventional integral imaging and an augmented reality technique. Compared with conventional integral imaging, our proposed system has two advantages: 1) it provides 3D augmented reality display capability and 2) it has a compact design. To validate the feasibility of our proposed method, we experimented with a 3D scene and used two computer-generated objects for augmented reality. By combining the captured 2D elemental images of the 3D object and the computer generated virtual objects, we reconstruct 3D images for the augmented reality micro integral imaging display system. To the best of our knowledge, the first report on a video see through 3D augmented reality display has been experimentally demonstrated with a micro integral imaging display system. The proposed 3D system has potential to be applied to the head mounted display system due to its small form factor.**

***Index Terms*—Augmented reality, displays, integral imaging, micro display, 3D display.**

I. Introduction

INTEGRAL imaging (also known as Integral photography) was first proposed by Lippmann in 1908 [1]. It has been resurrected and developed rapidly due to the development of digital imaging technology and devices [2]–[20]. Integral imaging systems include two processes: recording a 3D scene and reconstructing a 3D scene. A sensor array or a single camera with a lenslet array is usually used to record the intensities and directional information of a 3D scene. The recorded 2D images are referred to as elemental images where each image corresponds to a microlens. To reconstruct a 3D scene, elemental images are displayed on a display device and the rays pass through a lenslet array to reproduce the 3D scene in space. Integral imaging has been widely researched for various applications [2]–[20] due to its many advantages such as continuous view angles, virtual and real 3D display. Due to these advantages, integral imaging has been extensively investigated including design parameters analysis [6]–[12], methods to improve the performance of integral imaging such as viewing resolution [13], viewing angle [14], image resolution [15], and depth-of-field [16], [17].

Augmented reality is a technique used to superimpose virtual objects into a real scene so that they seamlessly blend into the real environment. It can greatly enhance the viewer's perception of reality [21]–[25]. This novel interactive technology has been used in architecture, medicine, military and even daily life. Thus, research integrating this technique in micro integral imaging display has many benefits. Augmented reality displays can be divided into optical-see through and video-see through devices [26]–[29]. With an optical see-through device, the real world is seen through half-transparent mirrors placed in front of the user's eyes. Computer generated images are reflected into the user's eyes. With a video-see through device, the computer-generated images are digitally combined with the images of the real world. In this paper, our device is a kind of video-see through display. Our proposed method can display real reconstructed 3D objects with augmented reality. In addition, by using a high resolution display panel and microlens array, our system is compact and suitable for specialized applications such as head mounted display system, manufacturing, TV surgery, or 3D microscopy among others.

We present a 3D augmented reality micro display system by combining the augmented reality technique with a micro integral imaging display. Compared with conventional integral imaging, our proposed system has two advantages: it can display real 3D augmented reality and it can be applied to the head mounted display systems [18], [28], [29] due to its compact design.

The paper is organized as follows. In Section II, the implementation of a micro integral imaging display system is described and display results are demonstrated using computer generated 3D objects. In Section III, experimental results of the augmented reality micro integral imaging display are demonstrated by using a real object and computer-generated objects, and Section IV contains the conclusions.

II. Micro Integral Imaging Display System

Unlike conventional integral imaging systems with large display panels and lens arrays, micro integral imaging systems require small display panels and small lenslet arrays. To realize such a compact augmented reality micro integral imaging display we used a liquid-crystal display (LCD) display panel (Epson Power Lite 6500UB) with resolution of 1080×1920 pixels and an 8.01 μm pixel size. The diagram of micro integral imaging display device is shown in Fig. 1. Two orthogonal

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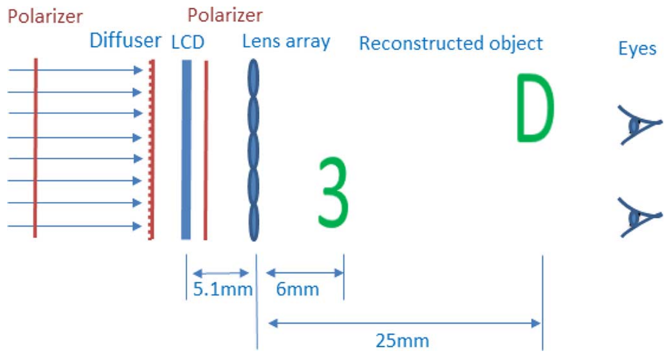

Fig. 1. Diagram of the micro integral imaging display.

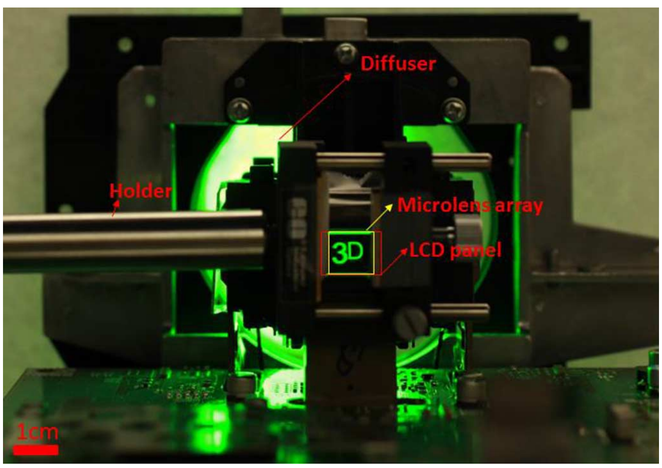

Fig. 2. Photograph of the micro integral imaging display system.

polarizers are used to control the LCD. One polarizer is placed in front of the LCD panel to generate polarized light; the other is placed behind of the LCD panel to filter orthogonal light. The diffuser shown in Fig. 1 can generate diffuse light for LCD panel. After illuminating the LCD panel which is displaying the elemental images, the light passes through a microlens array placed in front of the LCD panel to reconstruct the 3D scene. In the diagram, two letters "3" and "D" are reconstructed at different distances in front of the microlens array. We used a camera to capture the different perspectives of reconstructed 3D scene to verify our micro integral imaging display system. Fig. 2 shows a photograph of our micro integral imaging device and the specifications of our setup are shown in Table I. It is worth noting that the micro integral imaging display screen in our experiments is approximately 1 cm$\times$1 cm meaning that the system setup can be implemented in a compact form.

Using the micro integral imaging experimental setup, we implemented a 3D micro display experiment with computer generated elemental images using the software 2010 3ds Max to validate our micro integral imaging system. In the simulation, we place the letters "3" and "D" at 6 mm and 25 mm away from microlens array. The microlens array we simulated in 3ds Max has the same specifications as the real microlens array used in display stage. The display device is composed of a LCD display panel and a microlens array. The size of LCD display panel is 8.6 mm$\times$15.4 mm. To fully use the microlens array and the

TABLE I
SPECIFICATION OF THE MICRO INTEGRAL IMAGING SYSTEM

Virtual capture ("3" and "D")	Number of micro lenses	29(V) × 33(H)
	Lenslet Pitch	300 um
	Lenslet Focal length	5.1 mm
Real capture ("micro caliper")	Camera array	7(V) x 11(H)
	Sensor size	24 mm(V) × 36 mm(H)
	F number	2.5
	Each camera (# of pixels)	3744(V) ×5616 (H)
	Camera Pitch	1 mm(V) ×1 mm(H)
Display device	Numbers of micro lenses	29(V) ×33(H)
	Lenslet Focal length	5.1 mm
	Pitch	300 um(V) × 300 um (H)
	Lens Type	Plano Convex
	LCD panel (# of pixels)	1080 (V) × 1920 (H)
	Pixel size of LCD panel	8.01 (um)

LCD display panel, we use a 29$\times$33 microlens array in our experiment. Fig. 3(a) shows 29$\times$33 elemental images. These elemental images are displayed on the LCD panel. Computer reconstruction results are shown in Fig. 3(b) and (c). The computational reconstruction method can be written as the following [19]:

$$R(x,y,z) = \frac{1}{O(x,y)} \sum_{i=0}^{I-1} \sum_{j=0}^{J-1} E_{ij} \left(x - i\frac{N_x \times P}{S_x \times M}, y - j\frac{N_y \times P}{S_y \times M} \right), \quad \text{with } M = \frac{z}{g} \tag{1}$$

where $R(x,y,z)$ is the intensity of the reconstructed 3D image at a distance z from lens array, xx and y are the index of pixels, E_{ij} is the intensity of the ith column and jth row elemental images. I, J are the total number of elemental images in column and row. N_x, N_y are the total number of pixels in each elemental images, M is the magnification factor, g is the distance between the sensor and the microlens array, P is the pitch between image sensors, S_x, S_y are the size of the image sensor, and $O(x,y)$ represents the overlap of each point in the reconstructed 3D image. Fig. 3(b) and (c) shows the computationally reconstructed images of the letters "3" and "D" located at 6 mm and 25 mm. While, Fig. 3(d) and (e) shows optical experimental reconstructed images of the letters "3" and "D" with the micro integral imaging system located at 6 mm and 25 mm. We can see the letters "3" and "D" are clearly reconstructed in front of the micro integral imaging system. The horizontal and vertical parallax of the reconstructed 3D scene will be shown in the Section III.

III. 3D AUGMENTED REALITY MICRO INTEGRAL IMAGING DISPLAY

In order to realize 3D augmented reality in a micro integral imaging system, we integrate the displays of a computer generated object with a real world object. Here we choose a micro caliper (Craftsman 40181) as the real world object. And the simulated 3D scene consists of a letter "3" and "D".

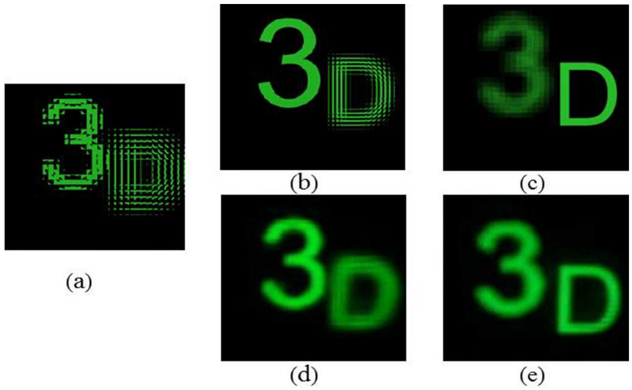

Fig. 3. Numerical and optical experimental reconstruction results of micro integral imaging system. (a) 29×33 Elemental images of computer generated letters "3" and "D". (b) Computational reconstruction of the letter "3" located at 6 mm. (c) Computational reconstruction of the letter "d" located at 25 mm. (d) Optical reconstruction of the letter "3" in front of 1 mm² integral imaging display. (e) Optical reconstruction of the letter "D" in front of 1 mm² integral imaging display.

In the experiments, 7×11 elemental images of the micro caliper are captured by moving a single camera (Cannon 5D Mark III) placed on a translation stage. Each elemental image has a resolution of 3744(V)×5616 (H). The field of view of each elemental image is 22.62 degrees. The moving steps of the stage in horizontal and vertical directions are both 1 mm. In our experiment, we only use the edge of the micro caliper for 3D display, which is shown in Fig. 4(a). Fig. 4(b) shows the total 7×11 elemental images.

In order to realize a 3D display with our micro integral imaging system using 7×11 elemental images, we converted these high resolution elemental images into 29×33 elemental images (the same number as the microlens array) shown in Fig. 4(c). This conversion was implemented using the smart pseudoscopic-to-orthoscopic conversion (SPOC) algorithm [20]. In addition, to enhance the display effect, we make the micro caliper reconstructed at 5 mm, very close distance to the letter "3", in front of microlens array. SPOC algorithm which allows full control over the optical display parameters in integral imaging monitors. For a given captured elemental images, one can generate a new set of elemental images to be displayed in an integral imaging monitor in which the pitch, the microlens focal length, the number of pixels per elemental image, the depth position of the reference plane, and even the grid geometry of the microlens array can be selected to fit the conditions of the display device.

To obtain the 3D micro augmented reality, we need to digitally mix the elemental images of the virtual object and the real object, as shown in Fig. 4(d). As the virtual object are commonly generated in computer with lamps to illuminate the 3D scene. The virtual object are blend into unwanted background. Many methods can be used to separate the aiming object with surroundings, such as K-means clustering [30], principle component analysis (PCA) [31], and threshold algorithms. In our experiment, due to the high contrast of objects and background, we can separate the aiming object with dark back ground by manually select a threshold. Therefore, we binarize the elemental images of the computer generated object by setting a threshold

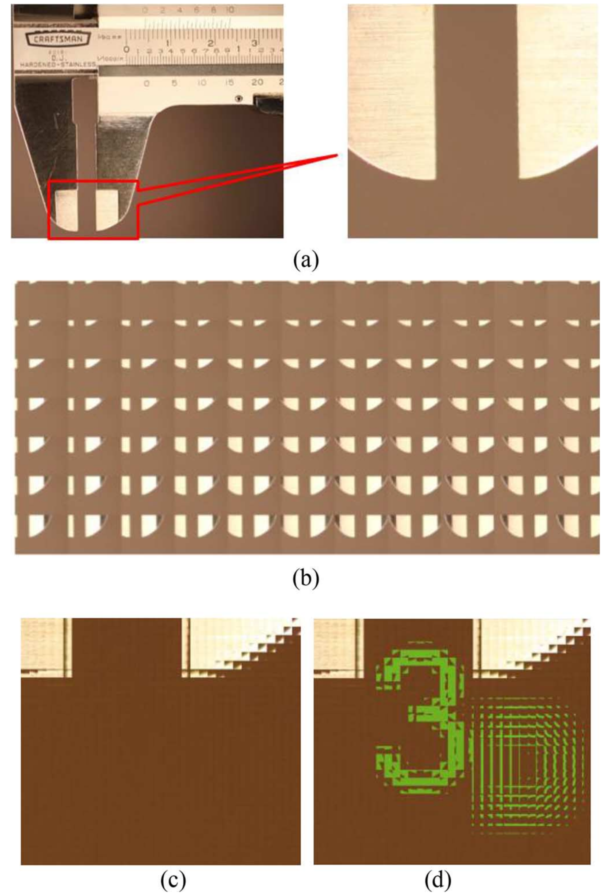

Fig. 4. Conversion and merger of computer generated and real world elemental images for 3D augmented reality. (a) A real 3D object (micro calipers). (b) Original 7×11 elemental images of the micro caliper. (c) Converted 29×33 elemental images of the micro caliper. (d) 29×33 elemental images for 3D augmented reality.

to separate the computer generated object and background. The image mixing method we used is mathematically described as follows:

$$I_{\text{binary}}(x,y) = \begin{cases} 0, & (x,y) \in \{I_1(x,y) < \text{thres}\} \\ 1, & (x,y) \in \{I_1(x,y) \geq \text{thres}\} \end{cases} \tag{2}$$

$$I_{\text{merge}}(x,y) = \begin{cases} I_2, & (x,y) \in \{I_{\text{binary}}(x,y) = 0\} \\ I_1, & (x,y) \in \{I_{\text{binary}}(x,y) = 1\} \end{cases} \tag{3}$$

where $I_1(x,y)$ and $I_2(x,y)$ are the intensity of elemental images of computer generated object and real world object, respectively. x and y are the index of pixels, *thres* is an intensity threshold to separate the computer generated object from its background. $I_{\text{binary}}(x,y)$ is the binary map of the computer generated object. $I_{\text{merge}}(x,y)$ is the final merged elemental image for 3D augmented display, which is shown in Fig. 4(d).

To avoid the degradation of reconstructed object when computer generated objects occlude the real object, one possible solution could be setting the computer generated object as half transparent.

Finally, we carry out a 3D augmented reality micro integral imaging display experiments. The augmented reality reconstructed images are shown in Fig. 5, which contains five images of reconstructed 3D scene from different perspectives. The

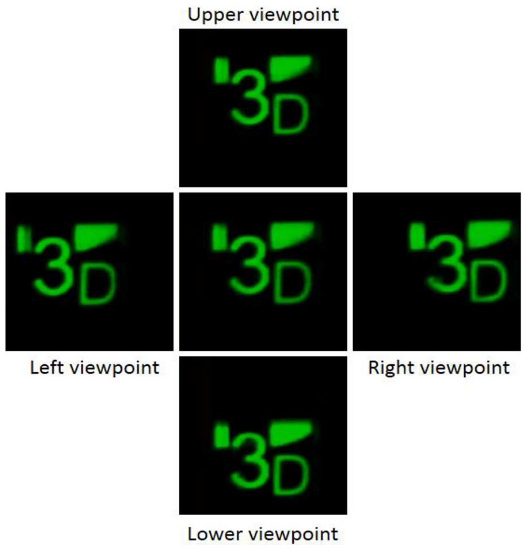

Fig. 5. 3D augmented reality micro integral imaging experimental results. Different perspectives of 3D augmented reality of micro integral imaging are shown. The letter "3" and the micro caliper are on the same plane. And the letter "D" is reconstructed in front of them.

letter "3" is reconstructed at 6 mm in front of the microlens array, while the letter "D" is reconstructed at 25 mm. From the left and right viewpoints, we can see that the distance between "3" and "D" becomes smaller. This indicates that the two letters have horizontal parallax, which means that the two letters are reconstructed at different longitudinal positions. Note that the reconstructed "D" is closer to us. We can also see the letter "D" moves slightly up from the top view to the bottom view, which indicates that the two letters have vertical parallax. These results demonstrate that our micro integral imaging display device can realize 3D augmented reality. According to Table I, we calculated that the field of view of a micro lens is 3.7 degrees. The large F number of the microlens are the main limitations to the viewing angle.

IV. Conclusion

We have presented a new application of integral imaging by combining the augmented reality technique into micro integral imaging 3D display. 3D augmented reality micro integral imaging experiment has been implemented to validate the feasibility of our proposal. The 3D scene is clearly reconstructed and has horizontal and vertical parallax. In addition the fact that our device is compact makes our system attractive for development in the future. Although the preliminary experimental result are only applied to a simple 3D scene, it has the potential and feasibility for more complicated micro dynamic scenes and applications.

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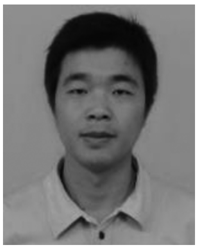

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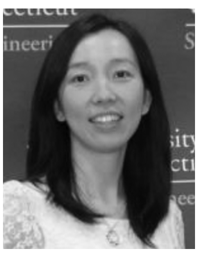

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