Passive and Active Optical Sensing for Three-dimensional Image Recognition

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ABSTRACT

Two techniques for recognizing three-dimensional(3D) objects based on passive and active optical sensing followed by numerical correlation are presented. One technique uses passive sensing of 3D object based on integral imaging and the other technique uses active sensing based on digital holography. In both techniques, the 3D data is stored in two-dimensional(2D) form as digital format and then the detected 3D information is used for recognizing 3D object based on 2D correlation techniques or neural network. Experimental results in both techniques are presented.

Keywords: Three-dimensional object, recognition, integral imaging, digital holography

1. INTRODUCTION

Tremendous development of computer technology, light source, imaging devices, spatial and temporal modulator enables us to handle the information of real or virtual 3D object by measuring, processing, displaying, and recognizing 3D object[1-19]. The measurement of surface structure or inside structure of a 3D object can be implemented by various methods such as triangulation and interferometer. These methods can be divided into two categories, passive and active sensing. Old technique such as triangulation is based on passive sensing. To obtain more information about 3D object such as inside structure, polarization profile, and spectral reflectance, active sensing is required. 3D object sensing is implemented by optical coherence tomography and holography. Measured information can be stored as digital format, thus we can use 3D object information for 3D object recognition. Combination of optical sensing and successive digital signal processing gives us a powerful tool to extract features of 3D object and enhance them. It would be helpful for recognizing 3D object.

In this paper, we present two techniques for recognizing 3D objects by use of passive and active optical sensing[4,6,10]. One technique uses passive sensing of 3D object based on integral imaging and the other technique uses active sensing based on digital holography. The detected 3D information is used for recognizing 3D object based on numerical correlation or neural network. Experimental results in both techniques are presented.

2. 3D OBJECT RECOGNITION BASED ON INTEGRAL IMAGING

We present here one possible system to recognize 3D objects by use of integral imaging. In the integral imaging system, a 3D object is recorded in an image sensor as an array of elemental images with different viewing angles by a lenslet array based on integral photography[4,6]. To record the elemental images, a 3D

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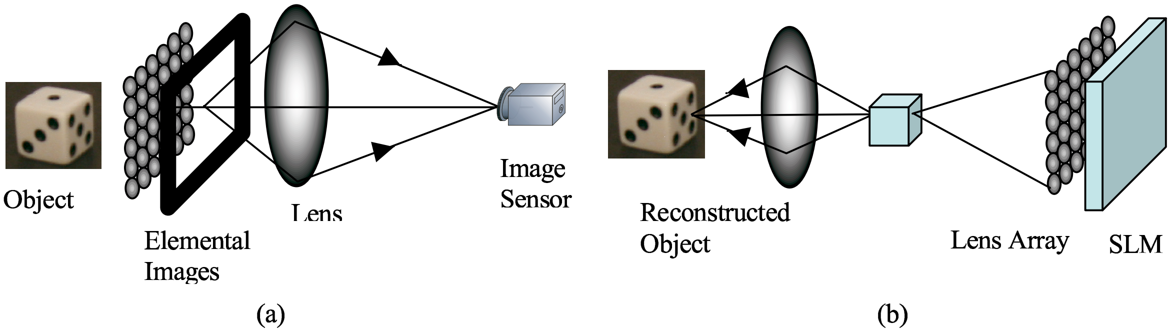
object itself can emit the light or a 3D object is illuminated by passive incoherent light source. This is passive optical sensing system. To detect other information such as stress[8] or spectral reflectance as well as 3D profile, the modulated illumination and its appropriate measurement should be required. In this case, the 3D sensing based on integral imaging can be active. Here we present a passive sensing system based on integral imaging.

Figures 1(a) and (b) show a 3D object recording and a reconstruction system based on integral imaging, respectively. The 3D object is recorded as elemental images by a two-dimensional lens array as shown in Fig. 1(a). Each elemental image has different view of the 3D object. After recording the elemental images by a film or an image sensor, the original 3D object can be reconstructed by illuminating the film or displaying the elemental images in a spatial light modulator because the light goes back the same way in the recording process as shown in Fig. 1(b). Therefore the integral imaging system can store the information of the 3D object as array of elemental images. In the 3D object recognition system, we use elemental images in the computational correlation for the recognition of the 3D object. Figure 2(a) and (b) show a part of elemental images of the reference 3D object and an input die with similar faces to the reference, respectively. In the experiments, we use two dice with dimensions 4.6mm × 4.6 mm × 4.6mm as a 3D input and a 3D reference. A number of lenslet array consists of 38 × 38 lenses with a period of 250 μm and a focal length of 1.3mm.

Joint transform correlation is used to recognize 3D object. Correlation between an input 3D scene and a reference 3D scene can be calculated optically or numerically. We present here the combination of optical method and numerical method to obtain the correlation signal. The joint power spectrum is recorded optically by making photographic film as an input image that consists of elemental images of the input 3D object and the reference object. We take the Fourier transform of the joint power spectrum in a computer and obtain the correlation of the object and the reference. Figure 3(a) and (b) show the autocorrelation and crosscorrelation of the input 3D object and the reference 3D object. We can see that the autocorrelation has a sharp peak, however the peak could not be seen in the crosscorrelation The crosscorrelation signal is 14.6 times smaller than the autocorrelation signal. Here the joint power spectrum is binalized to enhance the correlation signal. When the input 3D object is different from the reference object, the crosscorrelation signal is much smaller value than the autocorrelation signal.

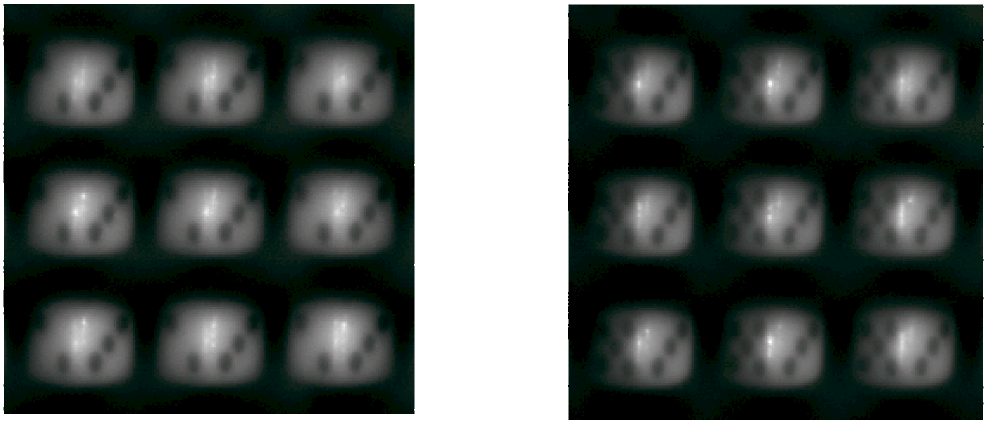


(a) (b)

Figure 1 An integral imaging system; (a) sensing system and (b) reconstruction system. SLM denotes spatial light modulator.

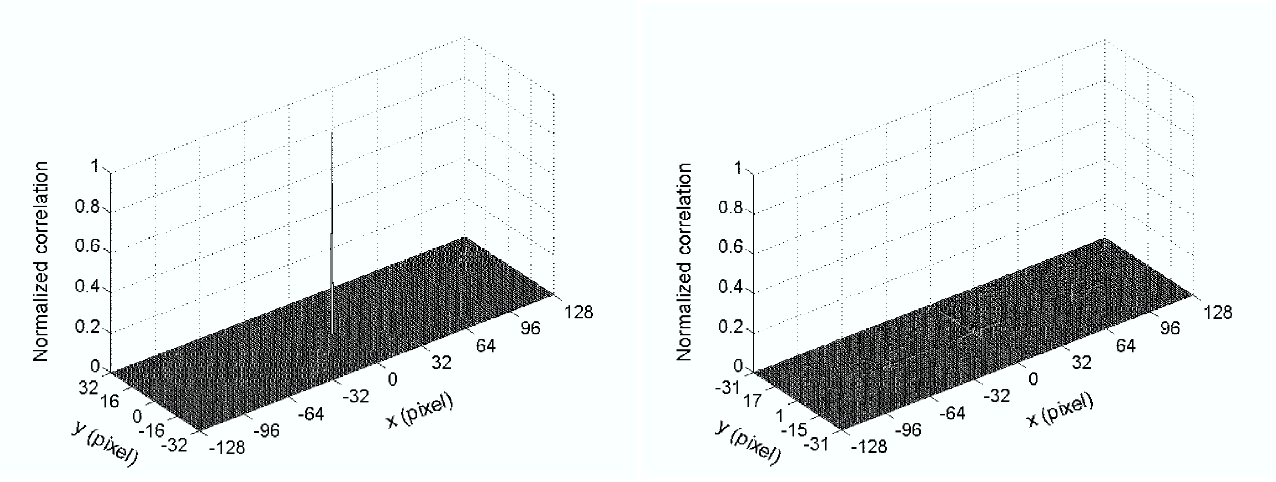
This system can also recognize a slightly rotated object and can evaluate the rotation angle. Figure 4 shows the projection of 3D input into elemental images. Each lens sees the input 3D object from different angles. When the input 3D object is rotated by appropriate angle, the elemental images are shifted. This spatial shift in the elemental images results in the shift of the correlation peak. Figure 5 shows the crosscorrelation profiles between the reference and the rotated reference with rotation angles of 0.26 and 0.78°. There are several sharp peaks. The highest peak located at 0 is the autocorrelation between the cubic structure of die.

The second highest peak corresponds to the rotation angle. When the rotation angle changes, we can see that the crosscorrelation peak shifts as shown in Figs. 5(a) and (b).



(a) (b)

Figure 2 Part of elemental images of (a) the reference and (b) the input with similar faces of the reference.

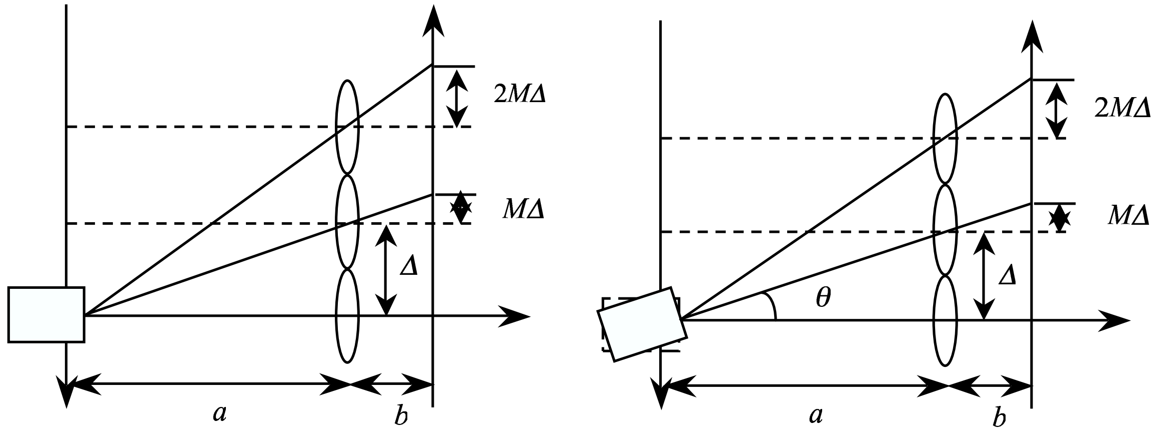


(a) (b)

Figure 3 Correlation results; (a) autocorrelation and (b) crosscorrelation with similar face.

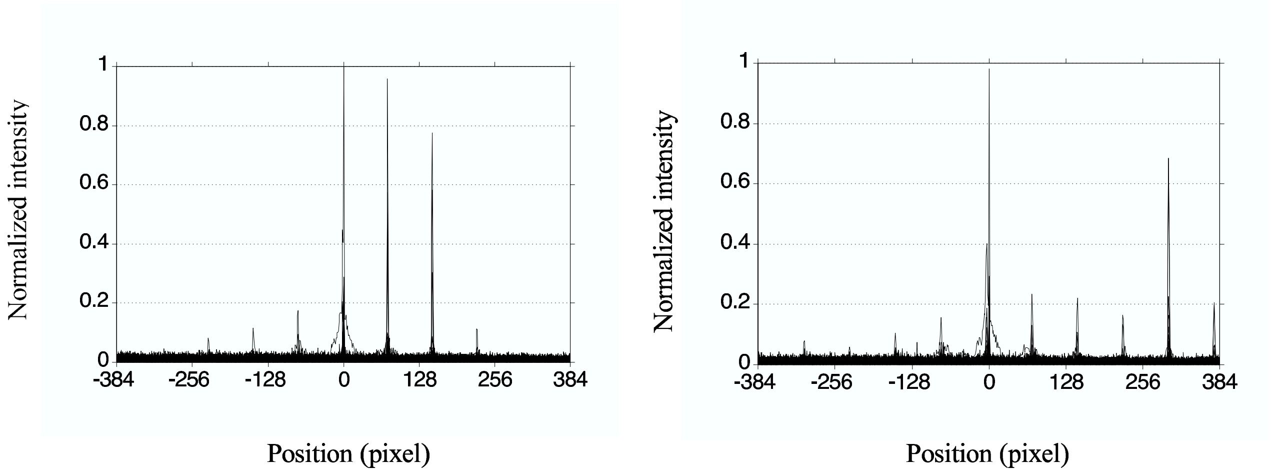
3. 3D RECOGNITION BASED ON DIGITAL HOLOGRAPHY

We present 3D object recognition systems based on phase shifting digital holography[4,10]. It is well known that holography can record the 3D information of the object because the amplitude and the phase distribution of optical wave can be recorded as hologram. Recently, the hologram is recorded as digital format in an image sensor instead of photographic plate. Conventional hologram reconstructs the 0-th order, the object wave and conjugate of the object wave. By use of phase shift digital holography, only the object wave or its conjugate wave can be reconstructed. The complex field of the 3D object at the detected plane can be used to implement the 3D object recognition[9]. We calculate the crosscorrelation between the complex fields of the



(a) (b)

Figure 4 Spatial shift of elemental images when the 3D object is rotated.



(a) (b)

Figure 5 Correlation profile when the die is rotated by an angle of (a) 0.26° and (b) 0.78°.

input and the reference 3D objects. The experimental results show that the correlation is highly sensitive displacement of the 3D object because of speckle noise caused by a rough surface of the 3D object. In the practical application, more flexible technique is required. We present here a 3D object recognition system by use of intensity distribution of reconstructed 3D object. The phase information is dropped, thus the correlation results becomes more robust. However it takes a long time to calculate 3D correlation by use of reconstructed 3D object. Therefore we use a reconstructed 2D image of the reference 3D object at an appropriate plane. A series of 2D correlation between the reference and a series of reconstructed input object is calculated. In this section we briefly introduce the phase shifting digital holography technique and then we show the calculation method of numerical Fresnel propagation. Finally we present the experimental results of 3D object.

Recently phase shifting digital holography[20] is applied into many applications such as measurement, display, and security systems. Development of image sensor with several hundreds million pixels enables us to record the hologram and obtain the complex field of optical wave reflected from 3D object. Figure 6 shows a typical configuration of four-step phase-shifting digital holography. A coherent light beam is divided into two beams, an object and a reference beam. The object beam illuminates a 3D object and then the reflected light propagates through free space. The object beam is interfered with the reference beam. The interference pattern is record as digital hologram by an image sensor. In four-step phase shifting digital holography, the phase of the reference beam is modulated by 0, π/2, π, 3π/2. The phase is modulated by a phase retarder such as waveplates liquid crystal modulator, and electro-optic modulator. When the object and the reference beams at the image sensor plane are denoted by U_o and U_r, respectively, the intensity pattern of the interference pattern is written by

$$I_n(x,y)=\left|U_o+U_r\exp\left(jn\frac{\pi}{2}\right)\right|^2 \tag{1}$$

with

$$U_o(x,y)=A_o(x,y)\exp\left(-j\phi_o(x,y)\right) \tag{2}$$

and

$$U_r(x,y)=A_r(x,y)\exp\left(-j\phi_r(x,y)\right)\ , \tag{3}$$

where n=0,1,2,3. By using four interference patterns, the amplitude and the phase of the object beam can be described as

$$A_o(x,y)=\frac{\sqrt{\left(I_0-I_2\right)^2+\left(I_1-I_3\right)^2}}{2A_r} \tag{4}$$

and

$$\phi_o(x,y)=\phi_r(x,y)+tan^{-1}\left(\frac{I_1-I_3}{I_0-I_2}\right). \tag{5}$$

When the reference beam is used as a plane wave, the calculation of Eqs. (4) and (5) is easy. In Eqs. (4) and (5), the calculation is implemented by the local information of the intensity at each pixel.

After the calculation of the optical field, we can reconstruct the 3D object in a computer or an optical system. Here we present a numerical reconstruction method. Fresnel propagation with a propagation distance z can be calculated by the following equation:

$$U(u,v,z)=\frac{\exp(jkz)}{j\lambda z}\iint U_o(x,y)\exp\left[-j\frac{k}{2z}\left\{(u-x)^2+(v-y)^2\right\}\right]dxdy\,. \tag{6}$$

The calculation method is changed according to the distance z because of the sampling theory. In the short distance, the Fresnel propagation can be calculated by convolution described by

$$U(u,v,z)=\frac{\exp(jkz)}{j\lambda z}\mathrm{FT}^{-1}\left[\mathrm{FT}\left[U_o(x,y)\right]\cdot\mathrm{FT}\left[\exp\left\{-j\frac{k}{2z}\left(x^2+y^2\right)\right\}\right]\right], \tag{7}$$

where FT^{-1}[•] and FT[•] denote the inverse Fourier transform and Fourier transform, respectively. In the long distance, the propagation can be calculated by one-time Fourier transform:

$$U(u,v,z)=\frac{\exp(jkz)}{j\lambda z}\exp\left\{-j\frac{k}{2z}\left(u^2+v^2\right)\right\}\mathrm{FT}\left[U_o(x,y)\exp\left\{-j\frac{k}{2z}\left(x^2+y^2\right)\right\}\right]. \tag{8}$$

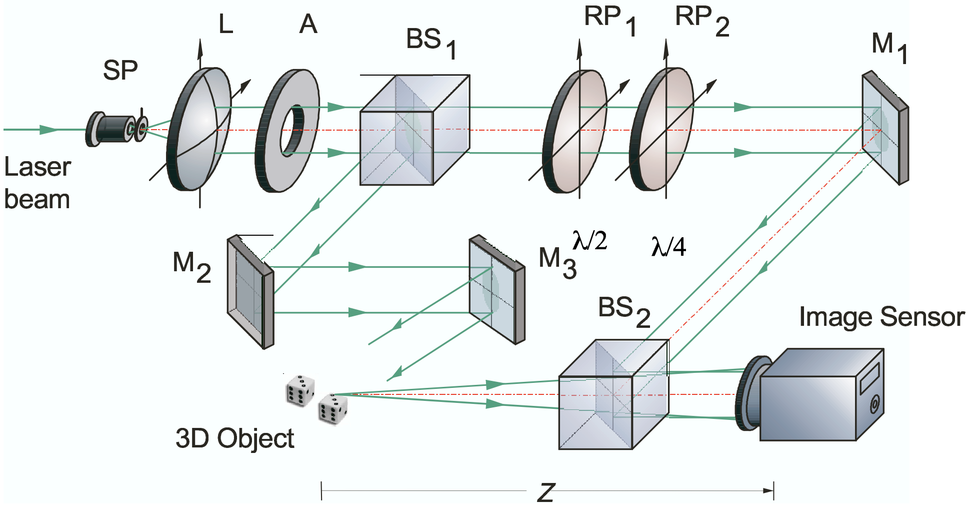
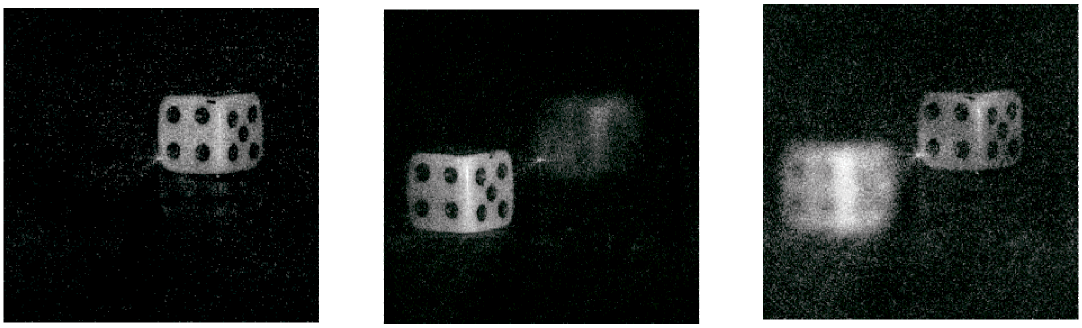


Figure 6 Schematic of four-step phase shifting digital holography; SP, spatial filter; L, lens; A, aperture; BS's, beamsplitter; M's, mirror; RP's, phase retarder plate.

In 3D object recognition, we use a reference 3D object and calculate the correlation between the reference and an input object. We present the experimental results of 3D object recognition. As in section 2, we use the same two dice with dimensions 4.6mm × 4.6mm × 4.6mm as a 3D input and a 3D reference. As the reference, a die located at 345mm is used. As the input, two dice located at 315mm and 345mm are used. The pixel size of image sensor is 9μm × 9μm. Figure 7 shows the numerical reconstruction of the die. Figure 7(a) is the reconstructed image of the reference 3D object at the propagation distance of 345mm from the image sensor. In the reconstruction of the input 3D object, we calculate the reconstructed image at various propagation distance, z. Figures 7(b) and (c) show examples of the reconstructed images at the propagation distance of 315mm and 345mm from the image sensor. We calculate 2D correlation between the reconstructed image of the reference and a series of the reconstructed images of the input. Figure 8 shows the correlation peak profile. We can see that there are two local maxima. One of the objects is located at the same position as the reference. The second one is located at 3D coordinate with respect to the reference object by (-7.7, -3.4, -30)mm. The peak of the second one is smaller than the first one. This is caused by the fact that the second object is not identical to the reference and is slightly rotated from the reference.

Because of the nature of holography, it is possible to reconstruct the image with different views of the 3D object by use of a noncentered window in the hologram plane. We can use this property to measure the rotation angle of the input 3D object with respect to the reference. Figure 9 shows the reconstructed images with three perspective angles of -0.9°, 0°, and 0.9° located at 315mm. We calculate the correlation between the reconstructed images in Fig. 9 and the reconstructed image of the reference. The correlation peak profile is shown in Fig. 10. We can see that the correlation peak is obtained at -0.9°(-544pixels). This means that the input die is rotated by -0.9° with respect to the reference die.

As mentioned above, the rotation tolerance is limited in small angle, about 1° because the effective numerical aperture is small in a lensless system. We have already showed that it is possible to enhance the rotation tolerance by use of nonlinear composite filter[11]. The classification capability is improved by use of neural network[12].



(a) (b) (c)

Figure 7 (a) Reconstructed images of the reference at 345mm from the image sensor and reconstructed images of the input at (b) 315mm and 345mm from the image sensor.

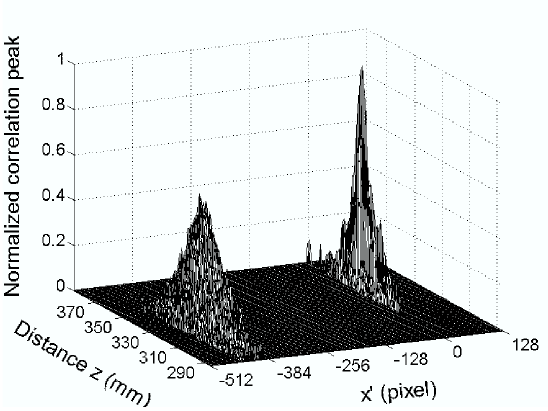
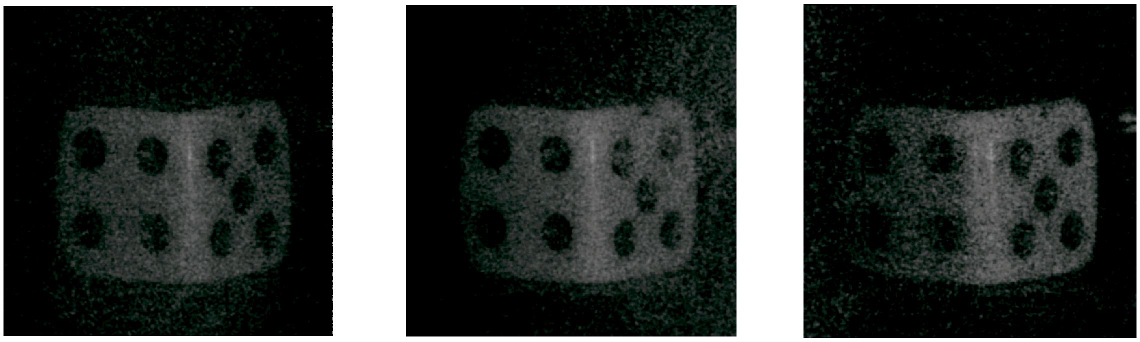


Figure 8 Correlation peak profile at various propagation distance.

4. CONCLUSIONS

In this paper, we have presented two systems for recognizing 3D object by use of passive and active optical sensing. To measure the 3D object information, we used integral imaging as passive sensing and phase-shifting digital holography as active sensing. Image quality in integral imaging is inferior to phase shifting digital holography. Integral imaging has advantages to phase shifting digital holography by the fact that the incoherent light source can be used, speckle noise is avoided, and one-shot measurement is implemented. Phase shifting digital holography can record high quality of 3D object. However three or four interference patterns are required to calculate the optical complex field. The sensing and the calculation of the optical field can be implemented in parallel, thus the system can be fast by making hardware with CMOS technology. Both methods can be active by use of the modulated light source, modulator, and appropriate detection system. Because 3D correlation takes a long time in the numerical calculation, we demonstrated 2D correlation based object recognition of 3D object. The experimental results showed that recognition capability of the present systems is high even when the similar object to the reference was used. The results also showed that rotation of the 3D object can be detected.



(a) (b) (c)

Figure 9 Reconstructed images at 315mm from the image sensor in different perspective angles of (a) –0.9°, (b) 0°, and 0.9°.

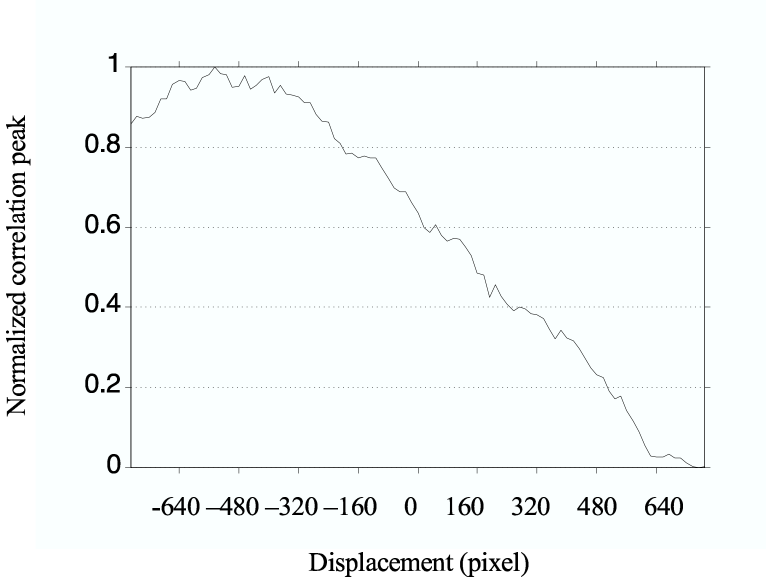


Figure 10 Maximum value of correlation between the reference and the input reconstructed images with different angle of views by use of noncentered window.

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