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3D Visualization of Objects under scattering media conditions using Integral Imaging

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***Abstract*— In this paper, we propose a new three-dimensional (3D) reconstruction technique in scattering media using integral imaging. In conventional integral imaging, it can visualize 3D images well when high-resolution elemental images are used. However, when low-resolution images are used, the visual quality of the 3D images is reduced. In addition, it is difficult to recognize the objects under scattering media conditions. Therefore, to visualize 3D images in scattering media, we create a mask filter in frequency domain to remove the scattering media. In addition, we calculate the density of the scattered media to adjust the contrast and histogram equalization automatically. To prove our method, we implemented optical experiments.**

Keywords—Three-dimensional reconstruction, Three-dimensional visualization, Integral imaging

I. INTRODUCTION

Recently, integral imaging has been used in many fields, including computer vision, unmanned autonomous vehicle, unmanned cameras, and so on, because integral imaging technique can extract the accurate depth information from two-dimensional elemental images. However, traditional 3D reconstruction techniques [1-5] in integral imaging may not recognize objects and generate accurate depth information under scattering media conditions.

To solve this problem, many researchers have been still studying the scattering media removal technique. However, it is still difficult to remove the scattering media with high scattering density [7-10]. In this paper, we propose a new scatter removal technique to enhance the visual quality of 3D reconstructed images. First, our method calculates the density of scattering media to calculate the visualization index and then analyzes the frequency spectrums for scattering media using Fourier transform of all elemental images and a mask filter. Then, we reconstruct the frequency spectrum of the 3D image without scattering media by a computational integral imaging reconstruction technique with filtered frequency spectrums of elemental images [6]. Then, we generate the 3D image by the inverse Fourier transform of the frequency spectrum of the 3D image. Finally, we adjust the contrast and use the histogram equalization automatically through the visualization index to enhance the visual quality of the 3D image.

This paper organized as follows. In Section 2, we introduce a 3D reconstruction technique volumetric computational reconstruction technique (VCR) [2-3]. In addition, we introduce the scattering media removal technique for integral imaging. In Section 3, we provide the experimental results to demonstrate that our method can recognize the object under scattering media conditions. Finally, we present a conclusion in Section 4.

II. SCATTERING MEDIA REMOVAL TECHNIQUE

Figure 1 shows the basic principle of integral imaging. Integral imaging has two primary processes. In the pickup process, integral imaging captures the various perspective 2D images of 3D objects through the lenslet array, where these 2D images are called as elemental images. Then, in the reconstruction process, 3D images can be reconstructed by back-projecting through the homogeneous lenslet array used in the pickup process. In this section, we present the volumetric computational reconstruction technique (VCR).

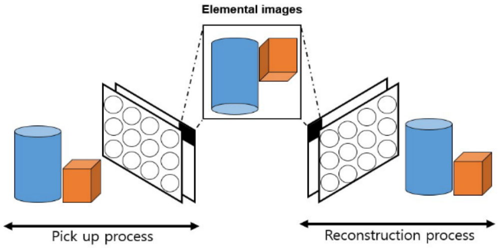

Fig. 1.Basic principle of Integral imaging.

A. Volumetric Computational Reconstruction (VCR)

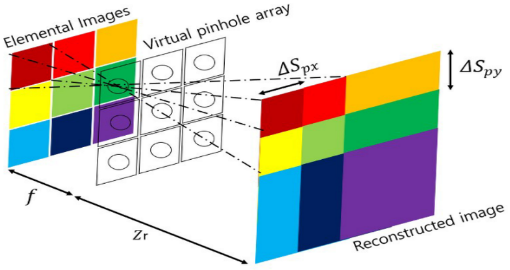

Fig. 2. Concept of VCR.

Figure 2 illustrates the concept of VCR. In this paper, elemental images are recorded by synthetic aperture integral imaging (SAII) [3] which is used to obtain high-resolution elemental images. These elemental images are passed through a virtual pinhole array and back-projected on the reconstruction plane. In addition, they are positioned by the shifting pixel value ΔS_{px}, ΔS_{py}. Finally, we can reconstruct 3D images using VCR as follows:

$$I(x,y,z_r) = \frac{1}{OV(x,y,z_r)} \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} I_{mn}\left(x + m\Delta S_{px}, y + n\Delta S_{py}\right) \quad (1)$$

$$\Delta S_{px} = \frac{Ei_x pt_x f_l}{cs_x z_r},\quad \Delta S_{py} = \frac{Ei_y pt_y f_l}{cs_y z_r} \quad (2)$$

where $OV_{(x,y,zr)}$ is the overlapping matrix for all elemental images, I_{mn} is mth column and nth row elemental image, Ei_x and Ei_y are the number of pixels of each elemental image in x and y directions, pt_x and pt_y are the distance between cameras, f_l is the focal length of the camera, cs_x and cs_y are the sizes of the camera sensor, and z_r is the distance between the virtual pinhole array and the reconstructed image, respectively. However, the VCR cannot reconstruct the accurate 3D object under scattering media conditions. Therefore, to reconstruct 3D images under these conditions, scattering media removal technique is required.

B. Scattering media removal technique

Previous scattering media removal method used the same Fourier mask filter without considering the density or quantity of the scattered media. Therefore, it was difficult to remove the scattering media effectively. On the other hand, in our proposed method, we calculate the density of the scattering media. It is defined as the visualization index in this paper. Finally, we use this visualization index for result 3D images to apply different contrast adjustment and histogram equalization for each elemental image.

Our proposed method can remove scattering media from the elemental images effectively and improve the visual quality of the reconstructed 3D image. We calculate the density of scattering media from the elemental images and define the visualization index for each scattering media condition. This visualization index is used to adjust the contrast ratio of the reconstructed image automatically.

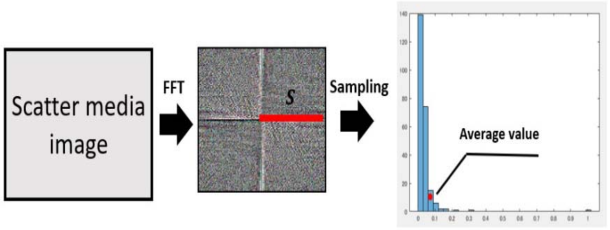

Fig. 3. Calculation process of average histogram value.

First, we need to calculate the visualization index from the histogram of elemental images under scattering media conditions. To calculate the visualization index, we find the Fourier transform of the elemental images, and then we calculate the density of the scattering media using a central elemental image. To analyze the scattering media density, we pick up the samples at Fourier domain from the center of the image to edge of the image. This is because, we can figure out the frequency distribution of elemental image. Then, we calculate the average histogram value of Fourier transformed image as shown in Fig. 3 and Eq. (3). In addition, It also helps to make a Fourier mask filter for remove scattering media.

$$K = \frac{\sum_{i=1}^{S_{num}} S_i}{S_{num}} \quad (3)$$

where S_{num} is the total number of sampling data, and S_i is the sampling value of each sampling data sequence. We defined the average histogram value of the scattering image as K. We also have to calculate the average histogram value of image without the scattering media, and we define this value as K_0. Finally, we define the scattering media density K' in Eq. (4).

$$0 \le K' = \left(1 - \frac{K}{K_0}\right) \le 1 \quad (4)$$

In addition, the object visualization index can be calculated by Eq. (5). The object visualization index V presents the degree of non-visualization of objects under scattering media conditions with distance.

$$0 < \mathrm{K}' \le \mathrm{V} \le 1 \quad (5)$$

We have to consider the depth of scattering media because objects under the same scattering media conditions are visible or invisible depending on the object distance. So, we construct a function which is density of scattering media via object distance, $f(Z_r)$. Finally, we can define the V by Eq. (6).

$$\mathrm{V} = \mathrm{K}' \times f(Z_r) \quad (6)$$

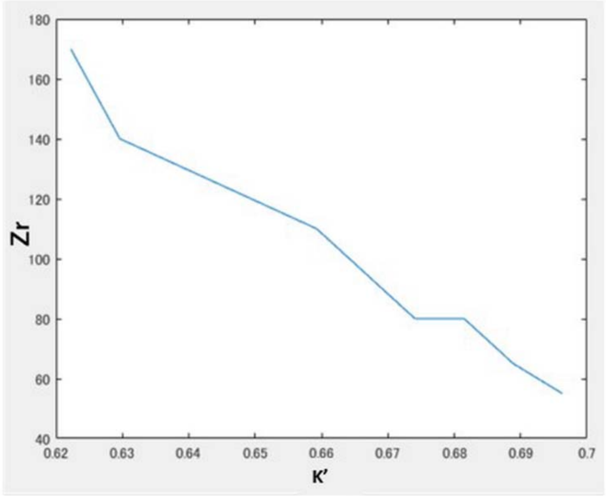

Fig. 4. Relationship between $\mathbf{K}'$ and $\boldsymbol{Z_r}$.

Figure 4 shows that the density of the scattering media increases as the depth of the scattering media increases. To obtain $f(Z_r)$, we assumed that V equals to 1.

$$\mathrm{K}' \times f(Z_r) = 1$$
$$f(Z_r) = \frac{1}{\mathrm{K}'} \quad (7)$$

With Eq. (7), we can derive the following graphs.

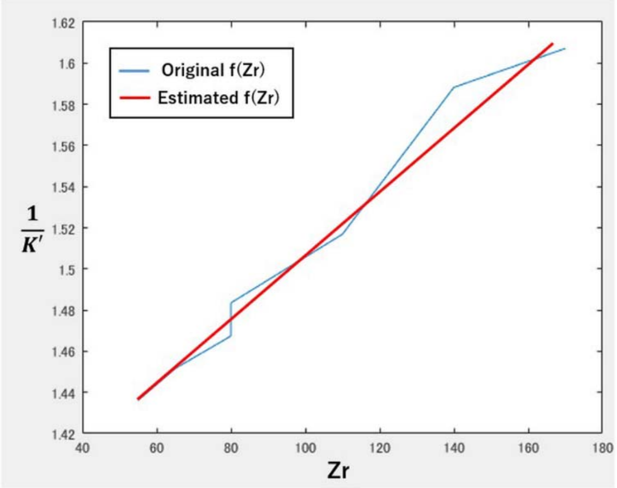

Fig. 5. Relationship between $\boldsymbol{f(Z_r)}$ and $\boldsymbol{Z_r}$.

Since the density of scattering media cannot increase linearly as blue line in Fig.5. Therefore, we use least square estimation to optimize $f(Z_r)$. The red line in Fig.5 represents the estimated $f(Z_r)$. Parameters, α and β, depend on the density and depth of the scattering media and can be defined by least square estimation. Finally, we can define $f(Z_r)$ as the following.

$$f(Z_r) = \alpha Z_r + \beta \tag{8}$$

When V is determined, VCR process is carried out using the Fourier Transformed elemental image as shown in Fig. 6.

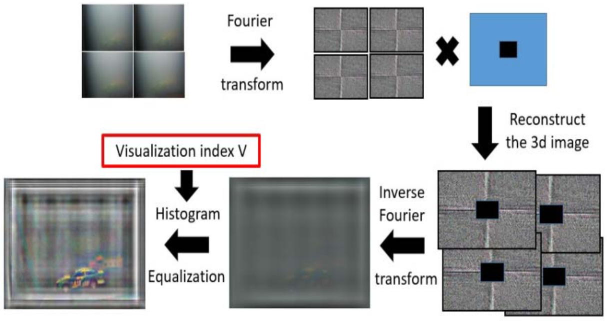

Fig. 6. Our proposed method image processing.

The proposed method transforms the elemental images to Fourier domain and then creates a mask filter that can remove the scattering media. We compose the Fourier mask filter through the histogram distribution. For example, there is no color or contrast change in elemental image under scattering media conditions. So, we can observe a lot of low-frequency components in sampling data. To reduce and remove these low frequency components, we composed the high pass filter in this condition. After that, we use VCR method in the Fourier domain to create the frequency spectrum of the reconstructed 3D image and use inverse Fourier transform to reconstruct reconstructed 3D image. Finally, we use the histogram equalization which use the visualization index value to adjust the reconstructed 3D image's histogram and contrast ratio automatically for recovering image more clearly and effectively.

III. EXPERIMENTAL RESULTS

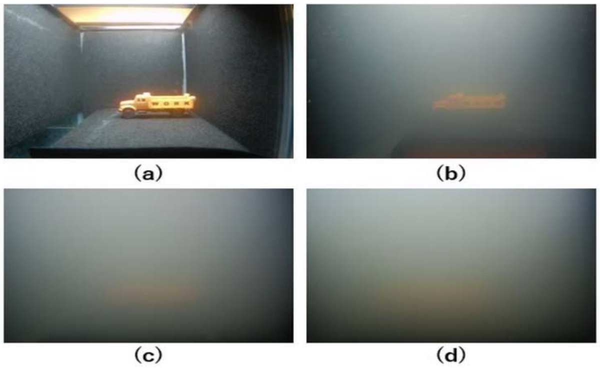

Fig. 7. Elemental images with different density of scattering media: (a) elemental image without scattering media, (b) elemental image with low density of scattering media, (c) elemental image with medium density of media, (d) elemental image with high density of scattering media.

We present the calculation result of scattered media density value K' first. We use the action camera which has a 640(H)×480(V) low-resolution and the focal length is 30mm. We used the transparent water tank, water, and milk to make turbid water environments like a haze. We changed the density of scattering media by pouring a certain amount of milk into the tank several times to check the K' value that varies with the density of the scattering media as shown in Fig. 7.

We can recognize the toy car in Fig. 7 (a) and (b). On the other hand, we cannot recognize the toy car in Fig. 7 (c) and (d) due to heavy turbidity. We calculate the K_0 using Fig. 7 (a), and we calculate the K value of Fig 7 (b), (c), and (d). Table 1 shows the result of scattering media density value K' using Eq. (4).

Table 1. Scattering media density value of each image.

Density value	Fig. 7 (b)	Fig. 7 (c)	Fig. 7 (d)
K'	0.631	0.703	0.749

We defined the density of scatter media as a value between 0 to 1. With these scattering media densities, we can get the visualization index for each scattering media condition, and we can adapt to histogram equalization and contrast ratio adjustment for each scattering media conditions.

Figure 8 illustrates the experimental setup to validate our proposed method. We used the same specification camera as the previous experiment, and we use the 5(H)×5(V) camera array. The distance between each camera is 3mm. Figure 9 shows the elemental images under the scattering media condition. K' value of each elemental image is 0.6 in this condition.

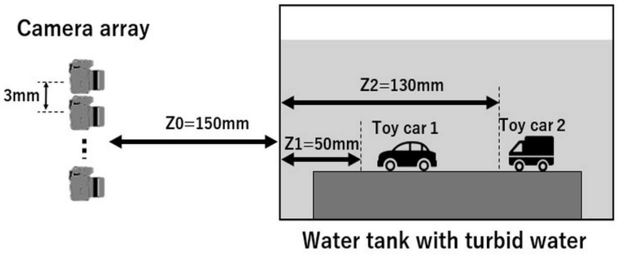

Fig. 8. Experimental setup.

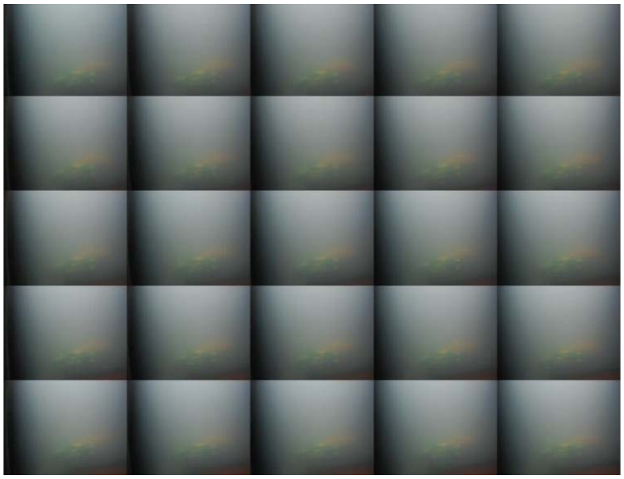

Fig. 9. Elemental images under scattering media condition.

We transform these elemental images to Fourier domain and remove the scattering media frequency of the elemental images. Then, we reconstruct the 3D image in Fourier domain by VCR. After that, we used inverse Fourier transform to obtain the reconstructed 3D image. Finally, we adjust the contrast ratio of the reconstructed 3D image and implement histogram equalization with visualization index V.

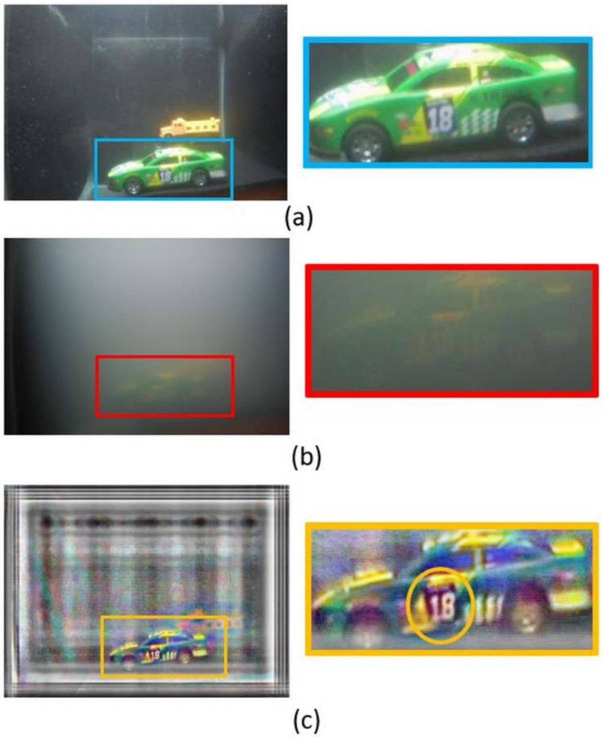

Fig. 10. The result images in 200mm: (a) the original image, (b) conventional VCR result image, (c) our proposed method result image.

Figure 10 shows the elemental image under clear water condition and the reconstructed 3D images under turbid water condition by conventional VCR and our proposed method, respectively. The reconstruction distance of Fig. 10 (b) and (c) is approximately 200 mm. We cannot recognize the green car shape in Fig. 10 (b). On the other hand, we can recognize the green car shape and the number 18 on the toy car in Fig. 10 (c).

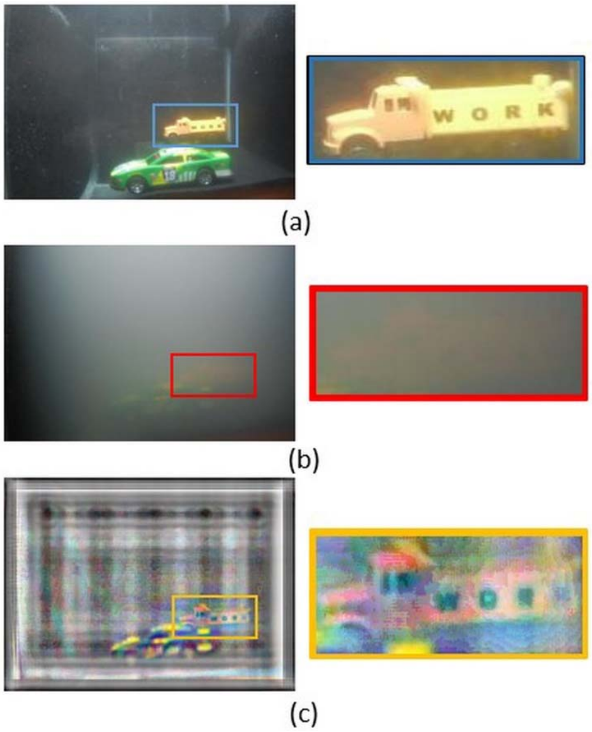

Fig. 11. The result images in 280mm: (a) the original image, (b) conventional VCR result image, (c) our proposed method result image.

Figure 11 shows the elemental image under clear water condition and the reconstructed 3D images under turbid water condition by conventional VCR and our proposed method. The reconstruction distance of Fig. 11 (b) and (c) is approximately 280 mm. We cannot see the words on the truck in Fig. 11 (b), but we can recognize the word “WORK” on the truck in Fig. 11 (c). It is noticed that our proposed method can remove the scattering media effectively.

IV. CONCLUSION

In this paper, we have presented the new scattering media removal method using integral imaging. Conventional integral imaging technique cannot generate the clear 3d image so we cannot recognize the object in the elemental image. However, our proposed method calculates the scattering media density and defines the visualization index of elemental images under scattering media conditions. The visualization index is used to adjust histogram equalization and contrast ratio. Finally, we can remove the scattering media from the elemental images effectively. Therefore, our proposed method can be used to unmanned cameras and autonomous vehicles in foggy environments. It may visualize the road image through the camera without any special equipment. However, when each elemental image has different scattering media density, our proposed method may not work well because it uses the same Fourier mask filter to remove the scattering media frequency of all elemental images. We will investigate a solution of this problem in future work.

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