https://doi.org/10.2352/ISSN.2470-1173.2018.04.SDA-248

Mobile integral imaging display using three-dimensional scanning

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Abstract

A three-dimensional mobile display based on computer-generated integral imaging technique for the real-world object using the three-dimensional scanning is proposed. The real three-dimensional information of the object is acquired by the three-dimensional scanning; then, the specification of the lens array is inputted by the user, and the acquired and inputted information are organized for the future processing. According to the acquired information, the virtual three-dimensional model for the object is generated, and the virtual space including a virtual model, a lens array, and imaging plane is configured. After the elemental image array is generated from the virtual model, the orthographic-view image and depth-slices are reconstructed and displayed on the mobile display according to the user interaction. The data organizing and image rendering processes are proceeded through the cloud computing due to the limited performance of the mobile device. The theory is approved experimentally, and the experimental results confirm that the proposed method can be an efficient way to display the three-dimensional visualization of the real-world object on the mobile display.

Introduction

Integral imaging is a popular light field three-dimensional (3D) imaging technique with the simple structure, and it is applied in various fields such as 3D camera, display and biomedical microscope [1, 2]. It can be categorized into main two parts: acquisition and reconstruction. In the acquisition part, a two-dimensional (2D) elemental image array (EIA) is captured through the lens array which consists of a lot of small lenses stuck with each other. Here, each elemental lens obtains the different viewpoint information, and accordingly, an entire EIA picks up the parallax, depth and color information of the object. In the reconstruction, the 3D volume image is reconstructed through the lens array which has same specifications with the lens array used in the acquisition. The reconstructed image provides full-parallax, full-color and continuous-viewing features. However, due to the imperfect matching of optical devices and lens aberrations such as distortion, the EIA is captured with low quality and it affects to the final reconstructed image quality.

The computer-generated integral imaging (CGII) is the effective solution for the issues mentioned above [3, 4]. It generates the EIA through the computer-graphics according to the inputted parameter such as virtual lens array specifications and the distance between lens array and EIA plane; so, the EIA is generated with perfect quality. So far, several CGII methods have been suggested [5-7], and based on the CGII techniques, many integral imaging display methods have been proposed, in order to improve the viewing characteristics, or fast-computation for EIAs [8, 9]. The main issue of the CGII is that it generates the EIAs only from the virtual objects.

Recently, G. Li et al. proposed the simplified lens array-free integral imaging pickup method using the depth camera [10]. The method acquires the full 3D information of the real-world object, depth, parallax, and color information, through the depth camera, and generates the EIA through the CGII method according to the acquired data. By applying the image space parallel processing algorithm which renders the images through graphic-processing unit (GPU) of user PC, instead of a central processing unit (CPU) [11-13], the method provides the real-time display [14]. Here, the EIAs are generated in very short time from the moving real-world object and displayed on the display device, while a lens array locates in front of the display device and reconstructs the 3D images. The system gives an opportunity to the users that acquires the 3D information of the real-world object without using the lens array, and generate the EIAs through CGII algorithm; so, the conventional problem of the integral imaging such as lens aberration does not occur. However, the system is proceeded only through the user PC, so it is impossible to apply in modern mobile device-based applications.

In this report, we proposed an integral imaging system on the mobile device using the 3D scanning method. Here, the 3D scanner acquires the real 3D information of real-world object, and produces the virtual 3D model of the object based on acquired information. From the produced 3D virtual model, the EIA is generated through a virtual lens array. From the EIA, the parallax and depth information of the object, the orthographic-view image and depth-slices, are reconstructed respectively. Due to the limited performance of mobile environment and large data of the object, the data organizing and digital reconstruction processes are proceeded through the cloud computing. In the experiment, it has been certified that the proposed method displays the fine-quality visualization of real object on the mobile device.

Background

Figure 1 shows the existing 3D data acquisition process from real-world object through depth camera [10]. The depth camera contains two different image sensors: a red-green-blue (RGB) and an infrared radiation (IR) sensors. A RGB sensor detects the color and texture information of the object, a common camera sensor as it. An IR sensor detects the real depth information of the object that the distance between each object point and the depth camera. Based on the acquired depth and color information, the virtual 3D model which is a visualization for the real-world object is generated. Here, the depth information should be converted due to the pseudoscopic image problem. The pseudoscopic image is one of the main issues of integral imaging technique that each object point is reconstructed at the same distance where it was located originally. In other words, the object points which was located at the near distance from the lens array, is reconstructed also at near

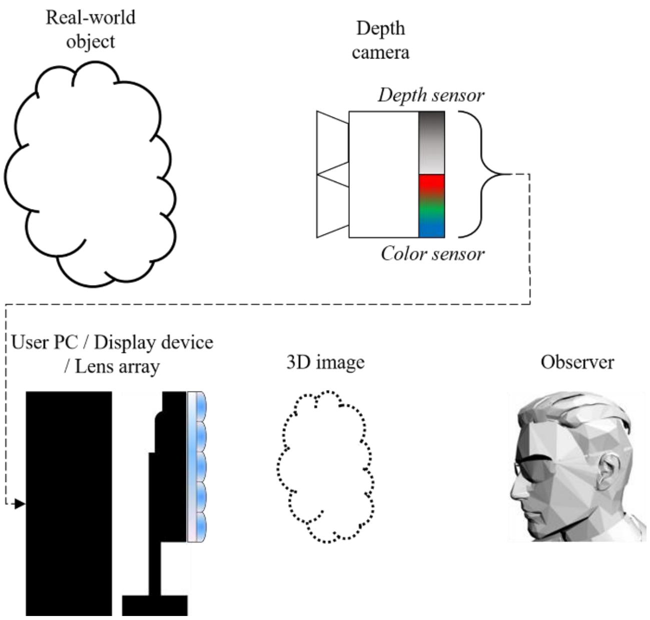

Figure 1. The schematic configuration of depth camera-based integral imaging pickup method

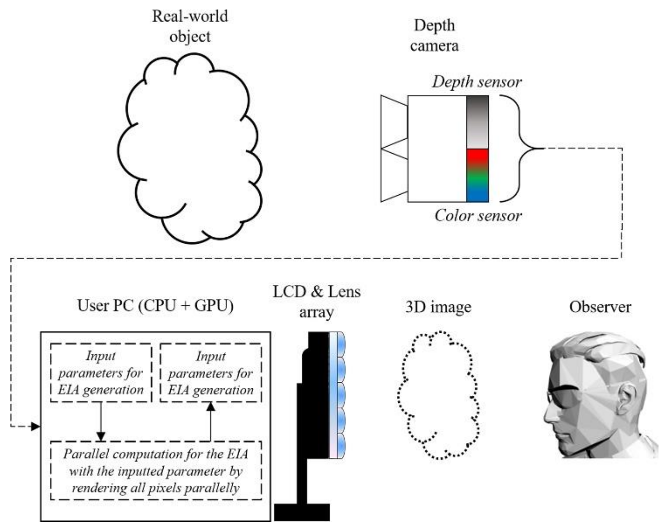

Figure 2. The scheme of depth camera-based real-time integral imaging display using GPU parallel processing.

distance from the lens array; and far object points are reconstructed at the long distance from the lens array. Finally, each object point is reconstructed with the inversed depth value.

Also, the acquired depth information through the depth camera is much wider than the depth range that the lens array can acquire/reconstruct properly; therefore, the overall depth information of the real-world object should be normalized, in order to be matched for the depth range of a lens array.

After the depth information is converted and normalized, the EIA is generated from the 3D virtual through the virtual lens array. Note that user inputs the specification of lens array such as the number, size and focal length of elemental lenses, and the central depth plane which is a distance between center of the 3D model and a lens array. Here, the light rays emanated from each object points are passed through each elemental lens center and imaged at the EIA plane as the pixels of EIA. The generated EIA is directly displayed on the LCD while the lens array is located in front of the LCD, and the 3D visualization of real-world object is reconstructed.

J.-S. Jeong et al. upgraded the theory as a real-time 3D integral imaging display for the real-world object [14]. The scheme of the real-time display system is illustrated in Fig. 2. The depth camera acquires the depth and color data of real-world moving object and the EIAs are generated via GPU parallel processing method, image space parallel processing algorithm. After the depth information is normalized and converted, and the lens array specifications are inputted, the main information of EIA such is the resolution, are calculated. The OpenCL kernel which is an application programming interface using the GPU cores and corresponding library, is utilized for EIA generation. Note that the OpenCL processes a lot of tasks simultaneously through the GPU cores, so it is widely used for pixel computation-based image processing methods where GPUs have much more number of cores than CPUs. Also, a GPU only renders the images, and rest of the basic processes such as parameter input and displaying the EIA, are proceeded through the CPU.

In the experiment, the system has displayed the full-parallax and full-color 3D animation (16 fps) with 4578×4578 pixels, where 30×30 lens array with 5 mm pitch and 10 mm focal length, a LCD with 0.1245 mm pixel pitch have been used.

Proposed method

The background systems have shown the lens array-free integral imaging pickup method and verified through the optical experiment, and presented the efficient experimental results, however, they have been performed through the PC-based computation only. Therefore, they are impossible to be applied directly for the day-to-day basis of application.

In this paper, we propose the 3D integral imaging mobile display using the 3D scanning for real-world object. Figure 3 shows the overall structure of the proposed method. The 3D scanning method acquires more accurate depth color information than previous systems, so, the quality of 3D reconstructed images can be better. In this scheme, first, the 3D scanner acquires the

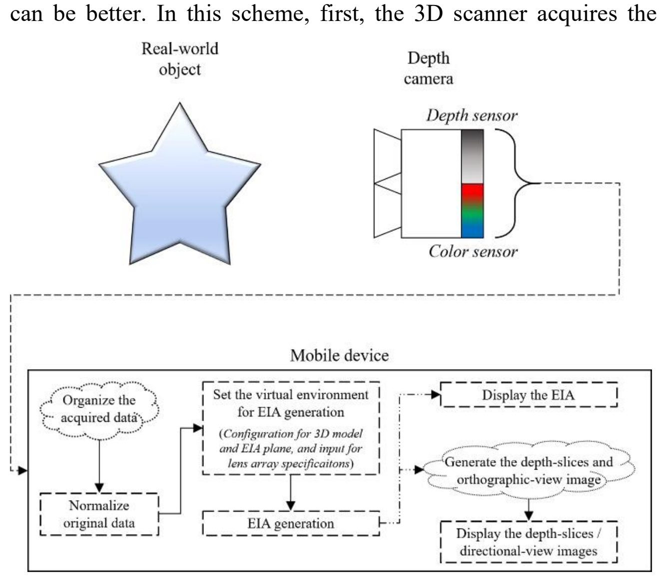

Figure 3. The schematic diagram of the proposed system.

original color and depth information of fixed real-world object. Then, the acquired information is transmitted to the mobile device and the virtual 3D model of the object is produced. From the 3D model, the EIA is generated through a virtual lens array with inputted specification. Finally, according to the application of the user, the 3D visualization of the real-world object can be reconstructed optically or digitally. The similar method has been conducted recently [15], but the proposed method uses the 3D scanning, instead of simply capturing the depth and color images.

The 3D scanner has same role and structure with the depth camera. It also consists of IR projection, and the RGB and IR sensors. In the existing methods, the depth camera has fixed in the specific location and object was captured in line with the depth camera. But in the acquisition stage of the proposed method, the object is fixed, and the 3D scanner scans the 3D information of real-world object, along the horizontal and vertical axes. It gives an opportunity that more precise 3D information and more number of object points can be acquired. Generally, the color information is captured as a common 2D image, and the depth information is saved as a coordinate for each object point with (x,y,z) values.

In the preprocessing stage, first, the originally acquired 3D information is organized, and the depth information is normalized, because the initially acquired depth information is much larger than the depth-of-field of lens array in which a 3D image can be acquired/reconstructed appropriately. If it is not normalized, some object points are imaged at the orthogonal planes which are placed too far or too near to the lens array, i.e., out of the boundaries of depth range of lens array; and it will cause the problem of defocused reconstructions. For any object point with (i,j) index, the depth value is normalized without any loss of original information, as following:

$$Z_{(i,j)} = \frac{2z_{(i,j)} \times z_{CDP}}{z_{\max} + z_{\min}} \quad (1)$$

where $z_{(i,j)}$ is an original depth value for each (i,j)-th object point, z_{CDP} is a central depth plane of 3D model, $z_{\max}$ and $z_{\min}$ are maximum and minimum values of the original depth information. The central depth plane, z_{CDP}, is determined by the Gaussian lens law which is given by $z_{CDP}=(g\times f_{LA})/(g\text{-}f_{LA})$, where f_{LA} is the focal length of a lens array and g is the gap between the lens array and the EIA plane. Figure 4 shows examples of initial and normalized depth information with the front-view of the 3D model where the acquired color information is covered on the 3D model. This depth-normalized 3D model is used in the EIA generation.

Optionally, when the 3D image will be reconstructed through the optical reconstruction method via a lens array, the normalized depth information should be converted for the proper visualization due to the pseudoscopic image conversion which is explained earlier. Here, Z values of each object point are converted to the reversed depth value, Z_I, within the normalized depth range, ΔZ, as following:

$$Z_{I(i,j)} = \frac{Z_{\max} + Z_{\min}}{2} + \left(\frac{Z_{\max} + Z_{\min}}{2} - Z_{(i,j)} \right) \quad (2)$$

where $Z_{\max}$ and $Z_{\min}$ are the maximum and minimum values of normalized depth information. Based on the depth conversion, the 3D object points are reconstructed at the proper distance from the lens array. Note that the depth conversion process is required only

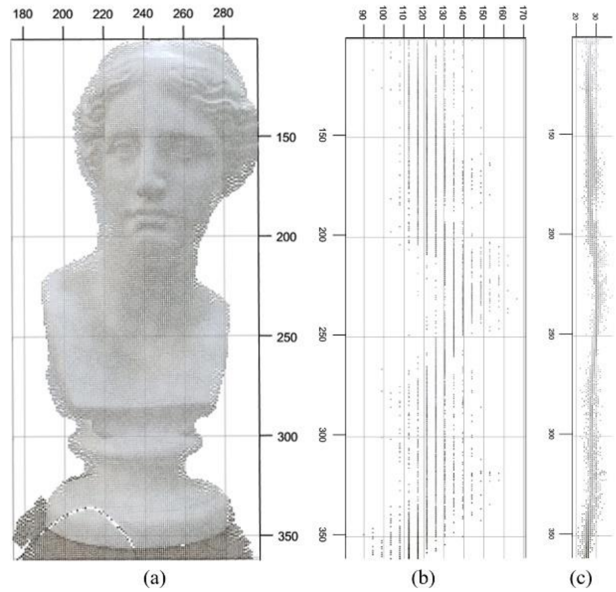

Figure 4. (a) For the given 3D model, (a) the visualization of original (Δz) and (c) normalized (ΔZ) depth information.

in the case of optical reconstruction of 3D image. When the digital reconstruction method is applied, for the depth and parallax visualizations, the EIA is generated directly from the normalized depth information.

Finally, in the preprocessing stage, the specification of the lens array, the number, focal length, and pitch of the elemental lenses, the gap between lens array and EIA plane, and the pixel pitch of EIA plane and/or mobile display are inputted. According to the normalized depth information and inputted parameters, the resolution of the EIA plane is calculated as:

$$EIA\left(EI_X, EI_Y\right) \Rightarrow EI_X = \frac{N_X \times P_{EL}}{P_D};\ EI_Y = \frac{N_Y \times P_{EL}}{P_D} \quad (3)$$

where EI_X and EI_Y are the size of an EIA according to the X and Y axes respectively, N_X and N_Y are the number of elemental lenses and elemental images according to the X and Y axes respectively, P_{EL} is the pitch of a single elemental lens, and P_D is the pixel pitch of the EIA plane which is identical to the pixel pitch of mobile display. All of these acquired, normalized, inputted and calculated data are organized, and transmitted to the mobile device.

Figure 5 shows the virtual environment for EIA generation includes the 3D model of real-world object, a virtual lens array and calculated EIA plane. The EIA generation process is proceeded in the mobile device. Each pixel the EIA is determined from the depth value of the object points, and the corresponding color intensity is converted on the corresponding pixel. If any color information is corresponded to the object points which is imaged through the lens array from the normalized depth information; this pixel will be imaged without color, visualized as a black. Unlike the existing depth camera-based methods, the OpenCL-based GPU parallel computation cannot be applied. So, in order to generate the EIA within possible short time, the multithreading method is applied. First, the threads with same number with the elemental images are created where each elemental image corresponds to a single thread. Due to the low number of CPU cores and limited

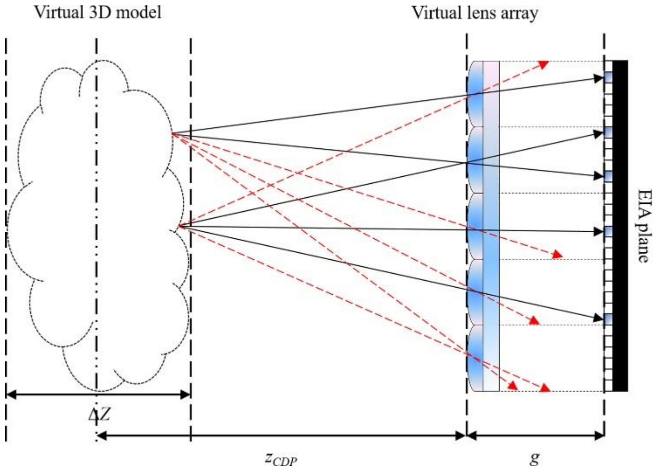

Figure 5. The EIA generation process in the mobile device, from the 3D model with normalized depth information, through the virtual lens array with inputted specifications.

performance of the mobile device, all of the threads cannot be proceeded simultaneously; so, the threads are ordered in a processing queue and they are processes by the order. Here, first few threads are processed while other threads are set in the ready-to-run mode, and after the active threads are processed completely, they are blocked. When the completely processed threads are blocked, the execution of the rendering process is switched to the next of ready-to-run threads in order, and switching process is iterated until all the threads are processed completely. Finally, the entire EIA is generated.

As mentioned above, the 3D image can be reconstructed through optical or digital reconstruction methods. In the optical reconstruction process, the generated EIA is displayed on the mobile dive while a lens array which has identical specifications with the virtual lens array, is placed in front of the mobile device; and a full-parallax continuous-viewing 3D image is reconstructed with original color information. Due to the additional depth conversion process, the reconstructed 3D image has proper depth visualization. And the overall depth visualization can be reconstructed due to the depth normalization.

Most of the modern mobile devices such as the smart phone and tablet PCs, use the touchscreen; but the touchscreen cannot be applied during the optical reconstruction, because of the use of a lens array. In order to use the touchscreen feature of the smart mobile devices, the digital reconstruction method is applied. It

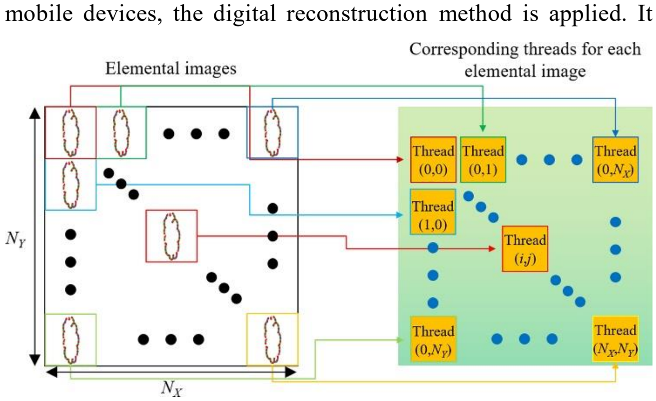

Figure 6. The scheme for the multithreading method of the EIA generation process.

includes the generations of orthographic-view image and depth-slices. Orthographic-view image presents the parallax-view of the real-world object [16]. It consists of the several directional-view images (sub-images), and each of them shows the different viewpoint of the object. The number of directional-view images is identical with the number of pixels which are belonged in a single elemental image; and the resolution of the single directional-view image is determined by the number of elemental images. The main advantage of the orthographic-view image reconstruction is that it presents the entire acquired viewpoints of the object can be visualized where the optical reconstruction presents the 3D image within the viewing angle which is narrower than orthographic-view image.

The depth-slices reconstruction presents the depth-of-field visualizations of the real-world object by the computational integral imaging reconstruction algorithm, and user can observe the desired depth plane [17]. The reconstructed depth-slices are almost similar to the optically reconstructed images, because the reconstructed depth-slices are based on the normalized depth-of-field and the input specifications of the lens array.

So, during the digital reconstruction method is applied, the user can select the desired viewpoint or depth-slide according to the user interaction, by using the touchscreen feature of the smart mobile devices. Note that the complex computation processes that difficult to be implemented in a mobile environment such as the data organization and digital reconstruction processes, are proceeded through the cloud computing.

Experimental results

Figure 7 shows the prototype of the proposed system and the

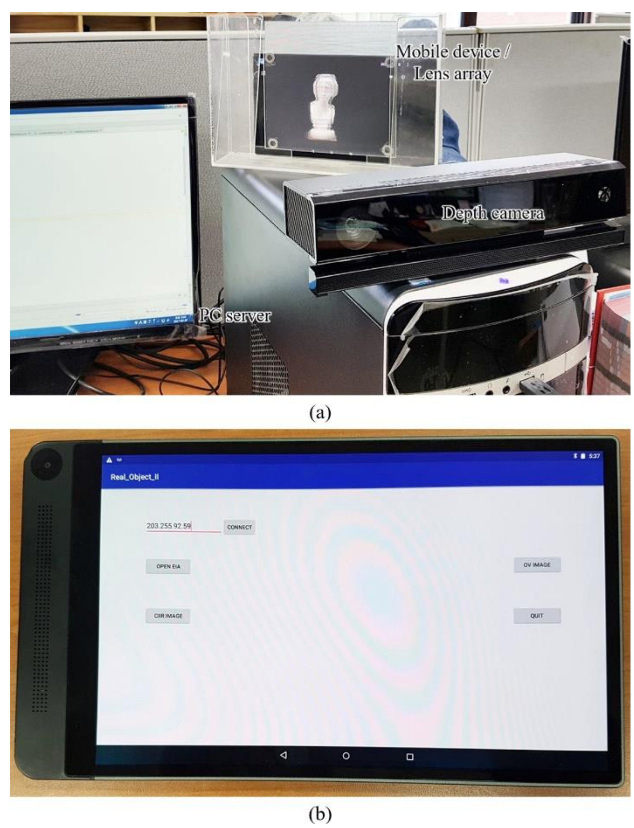

Figure 7. (a) The prototype of the proposed system, and (b) the user interface of the host program on the mobile device.

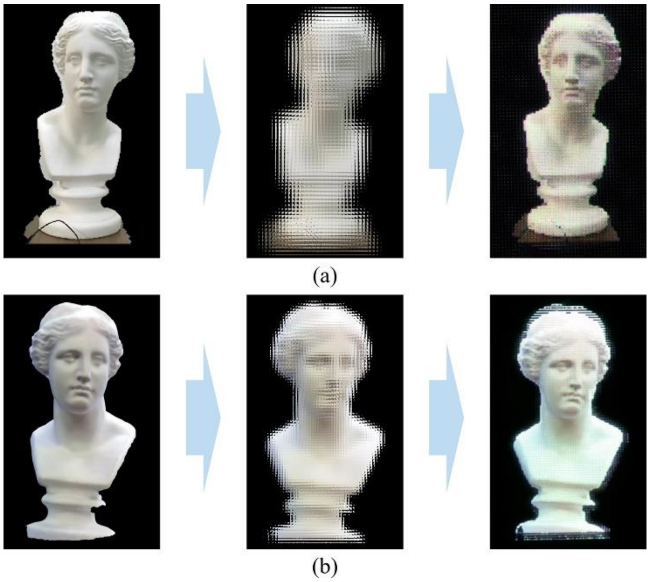

Figure 8. The original view, generated EIA and optical reconstructed 3D visualization for the real-world object: in the case of (a) exiting and (b) proposed methods.

user interface of the host program on the mobile device. In the experiment, the Dell Venue 8 7840 tablet PC with a resolution of 2560×1600 pixels (CPU: Intel Z3580 quad-core, 2.33 GHz; RAM: 2GB; Pixel pitch: approximately 0.07056 mm), and a lens array consisting of 150×150 elemental lenses with a focal length of 3.3 mm and a pitch of 1 mm has been utilized. An Intel RealSense F200 depth camera with 1920×1080 pixels of resolution for the RGB sensor and 640×480 pixels for the IR sensor has been applied as a 3D scanner. We used a PC server as a cloud computing for the experiment where a server and mobile device have been connected

Figure 9. The example of the directional-view images: the central viewpoint and top, bottom, left and right marginal images.

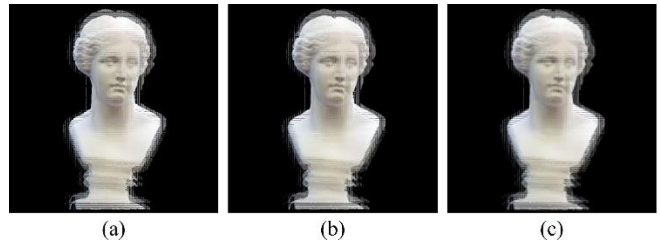

Figure 10. The example of the reconstructed depth-slices: (a) ΔZ=7.2 mm, (b) ΔZ=9.7 mm, and (c) ΔZ=12.2 mm where z_{CDP} is calculated as 9.7 mm.

via wireless connection where the wireless connection was supported by 802.11n wireless standard with 150 Mbps theoretical maximum speed. In the experiment, the PC server proceeded the preprocessing stage and digital reconstruction.

The real-world object “Statue” is used in the experiment. After the 3D scanning, total 118466 object points has been acquired. In order to compare the experimental results with existing fixed depth camera-based integral imaging methods and mobile integral imaging system, we also captured the object by the fixed depth camera. By the acquiring the depth and color information of the object through the existing method, 29085 object points have been acquired. So, it can be seen that the proposed method acquires more object points than previous methods.

Figure 8 shows the original object, the generated EIA and the optically reconstructed image for the object. Figure 8(a) shows the experimental results by the existing methods and Fig. 8(b) shows the experimental results by the proposed method. Here, the EIAs were generated with 2126×2126 pixels of resolution. In case of existing method, the object size was acquired certain small, so, in order to get the sufficient size of EIA, the additional scaling process has been utilized. But for the proposed method, initially acquired data was enough for the next processes. From the right-side images of Fig. 8, it can be seen that the proposed method provides the much clearer 3D images than previous methods.

Figure 9 shows the examples of the displayed directional-view images, top, bottom, center, left and right viewpoints, within the reconstructed orthographic-view image. Here, the reconstructed orthographic-view image has included 14×14 directional-view perspectives where the resolution of each directional-view image was 150×150 pixels. According to the user interaction by using the touchscreen of mobile display, the different directional-view images were displayed.

Figure 10 shows the example of the reconstructed depth-slices. In the experiment, the parameter z_{CDP} has been calculated as 9.7 mm where f_{LA}=3.3 mm and g=5 mm. The eleven depth-slices were reconstructed within 5 mm of depth-of-field, from 7.2 mm to 12.2 mm, in the interval of 0.5 mm. By using the seekbar under the image area, user could change the depth-slices and observed the desired depth images.

From the reconstructions, especially in the digital reconstruction, it has been verified that the lens array-free 3D visualization of the real-world object, the parallax depth visualizations, were successfully reconstructed on the user interaction-based mobile device.

Conclusion

We propose the 3D acquisition and display method on the mobile device based CGII and 3D scanning methods. 3D scanning method acquires more accurate 3D information of the real-world object, and EIA and reconstructed images provide the improved quality. After the 3D information is acquired, the original depth data is normalized into the lens array's depth range, and these data are transmitted to the next buffer with inputted parameters. Additional depth conversion process requires when the optical reconstruction method is applied. The EIA is generated by use of the organized data and inputted parameters, and displayed on the mobile device directly, when the optical reconstruction method is applied. If the digital reconstruction method is utilized, the orthographic-view images and depth-slices are reconstructed from the EIA. Here, the user can select the desired directional-view image or depth-slide according to the user interaction. Experimental results confirm that the proposed method can be an efficient way to acquire and display the 3D images from real-world objects on the mobile device. Further work focuses on complete cloud computing-based processing, and improvement for the image quality and computational speed.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (No. NRF-2017R1A2B4012096) and supported by the Korea government, under the ITRC (Information Technology Research Center) support program (IITP-2017-2015-0-00448) supervised by the IITP (Institute for Information & communications Technology Promotion).

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