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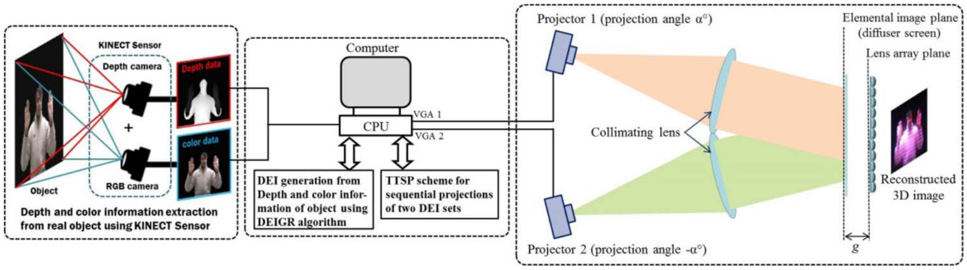

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Viewing-Angle-Enhanced Integral Imaging Display System Using a Time-Multiplexed Two-Directional Sequential Projection Scheme and a DEIGR Algorithm

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Abstract: We propose and demonstrate a viewing-angle-enhanced integral imaging display (VAEIID) system that uses a time-multiplexed, two-directional sequential projection (TTSP) scheme and a directional elemental image generation and resizing (DEIGR) algorithm. The main idea behind the method is sharing the same image screen to display two-directional elemental image (DEI) sets with a time-multiplexed sequential projection scheme. The proposed system consists of three processes: acquisition of depth and color information of a real object using the Microsoft Kinect sensor, generation of two DEI sets considering two different angular perspectives using a DEIGR algorithm, and projection of two sets of DEIs using the TTSP scheme. Due to the two-directional projections, each elemental lens of the lens array collects two-directional illuminations from the two sets of elemental images (EIs) projected in a time-multiplexed sequential manner by using the TTSP scheme; this produces two point light sources (PLSs) at different positions on the focal plane of the lens array. The positions of the PLSs are predefined and are determined in terms of projection angle. In this case, the viewing angle comprises the combination of two diverging ray bundles emerging from the two DEI sets projected from two angular directions. As a result, the viewing angle of the proposed VAEIID system is enhanced by almost twice that of the conventional method.

Index Terms: Integral imaging, VAEIID system, TTSP scheme, DEIGR algorithm, directional elemental image (DEI).

1. Introduction

Integral imaging (II) is a promising autostereoscopic 3-D display technique that provides a full-color, full-parallax, 3-D image with continuous viewpoints without the need for any supplementary glasses or tracking devices to perceive the 3-D scene [1]–[10], which distinguishes II from other 3-D display technologies. Recently, II has attracted a great deal of attention from many researchers because of its attractive advantages and applications. Despite a number of tremendous benefits, II has suffered from some major drawbacks, such as insufficient resolution and a narrow viewing angle and shallow image depth that are restricted by the specifications (i.e., lens pitch, focal length, etc.) of the lens array used. Among those limitations, the narrow viewing angle is the most serious drawback in II, which is a barrier to commercial implementation. The limited viewing angle in II is due to a limitation in the area where each elemental (constituent) image can be displayed. A small f-number in the elemental lens of lens array is desirable to increase the viewing angle, but the f-number of the elemental lens cannot be satisfactorily small because of the lens aberration. On the other hand, the lens width cannot be arbitrarily large because a large lens size reduces the number of lenses that can be accommodated by a given display panel size, and reduces the 3-D effect. A lot of research has been conducted to minimize or solve the limitation in viewing angle, such as the lens switching method [11], the curved lens array technique [12], moving lenslet arrays with a low fill factor [13], micro-convex-mirror arrays [14], the multiple-axis telecentric relay system [15], two display devices and a lens array [16], and a 3-D/2-D convertible integral imaging display using double collimated or non-collimated illumination [17]. Although those techniques can improve II, they cannot satisfactorily overcome the limitations with an appropriate scheme that can be commercially implemented. Some other effective techniques have been demonstrated to overcome this problem. Choi et al. demonstrated a multiple-viewing-zone II display using a dynamic barrier array that produces multiple viewing zones by guiding the light rays emanating from the elemental images (EIs) using a dynamic barrier array [18]. Although this technique verified the possibility of generating multiple viewing zones by guiding rays from EIs, the system is not suitable for real-time operation because of low speed and inefficient mechanical movement. Baasantseren et al. proposed a wide-viewing-angle II display using two EI masks [19]; in this method, light rays emitted from EIs are directed by two masks into corresponding lenses.

Recently, we developed a new method that is capable of controlling the viewing zone of the integral imaging display by using a directional projection of EIs at a predefined projection angle; the viewing zone shifts in terms of the projection angle [20]. In this method, a special type of elemental image-generation algorithm—i.e., a directional elemental image generation and resizing (DEIGR) algorithm—was introduced based on a pixel-mapping algorithm by considering the directional projection geometry for each pixel according to the directional projection angle, and an elemental image resizing function was applied to the EI generation algorithm to resolve the mismatch between the EI and elemental lens pitch of the lens array, which occurred due to the directional projection. Unlike the systems demonstrated by Choi *et al.* and Baasantseren *et al.*, the proposed system does not require any barrier array or masks to tilt the rays emerging from the EIs. It can independently direct the light rays emerging from the EIs with a directional projection (collimated) method without any ray-guiding equipment or technique. On the other hand, although the lens switching method [11] demonstrated by Lee *et al.* can effectively enhance the viewing angle by opening and shutting each lens in the array sequentially using moving masks, this method is not suitable for enhancing a large viewing angle because of the limited ray divergence possible with this method without using advanced ray guiding equipment [18], [19].

In this paper, we propose a viewing-angle-enhanced integral imaging display (VAEIID) system and implement it by using a time-multiplexed, two-directional sequential projection (TTSP) scheme and a DEIGR algorithm. The proposed VAEIID system is composed of three main parts: acquisition, processing and display. The depth and color information of a real object are acquired by using the Microsoft Kinect sensor [21]; then, two sets of directional elemental images (DEIs) are generated by synthesizing the extracted depths and color information of the real object for two different angular perspectives using the DEIGR algorithm; and finally, these two sets of DEIs are projected through the proposed VAEIID system in a time-multiplexed sequential manner with two digital light processing (DLP) projectors using a TTSP scheme. In the proposed method, the viewing angle comprises the combination of two diverging ray bundles emerging from the two sets of DEIs projected on a common image screen (i.e., a diffuser screen) which provides a wider elemental image area (i.e., twice that of a conventional system) for each elemental lens of the lens array, whereas a conventional II display system provides an elemental image area equal to the elemental lens pitch for each elemental image. (Note that, in

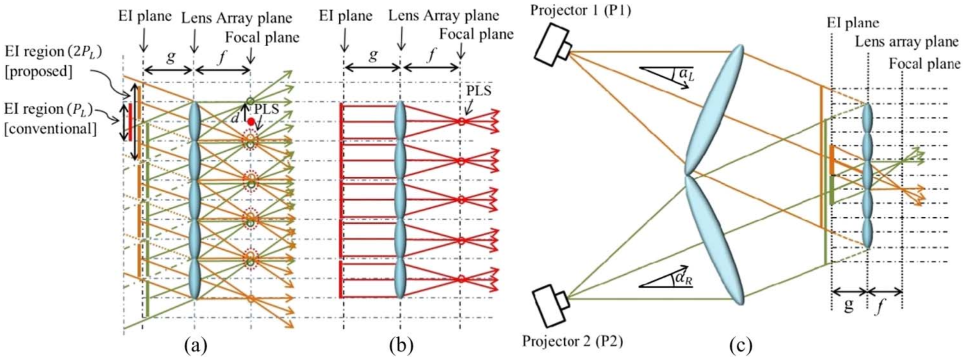


Fig. 1. Principle for viewing angle enhancement with the proposed method. (a) Basic principle of the proposed method (i.e., PLS shifting by the directional projection and formation of a wider angle of the diverging rays due to the two directional elemental image projections), (b) basic principle of the conventional method, and (c) mechanism of the two-directional projection scheme with two projection devices.

a conventional II system, the EIs are projected at a 0° angle with the optical axes of the lens array.) As a result, the viewing angle of the proposed VAEIID system is enhanced by almost two times that of the conventional method.

2. Proposed Method

2.1. Principle

Fig. 1 illustrates the principle of the proposed method. By using the TTSP scheme, two sets of DEIs are projected in order to retrace them though the same lens array from two different angular (i.e., α_L and α_R) directions in a time-multiplexed sequential manner. Hence, a wider angle of ray divergence is achieved due to widening the EI space (i.e., twice of the elemental lens pitch, $2P_L$) for each elemental lens with the projection of two sets of DEIs from two different angular directions; whereas in a conventional II system, the EI space for each elemental lens is equal to the lens pitch (i.e., P_L), as shown in Fig. 1. As a result, the viewing angle of the proposed VAEIID system forms as the combination of two diverging ray bundles emerging from the two sets of DEIs.

The two directional projection angles are determined such that each of them can shift the point light source of an elemental lens of the lens array by a half of the lens pitch ($\frac{P_L}{2}$); i.e., the displacement ($d = \frac{P_L}{2}$) of each PLS from the optical center of the lens should be half of the lens pitch, and they are placed opposite each other from the optical center of each elemental lens of the lens array. The principle of PLS shifting by directional projection and the formation of a wider angle of the diverging rays due to the two directional elemental image projections are depicted in Fig. 1(a)–(c). In the proposed method, it is very important to determine suitable directional projection angles. To achieve an enhanced viewing angle of almost two times the conventional method, the two directional projection angles can be determined depending on the parameters of the display components of the VAEIID system from the following expressions:

$$\alpha_L = \tan^{-1}\left(\frac{P_L}{2f}\right) \text{ and } \alpha_R = -\tan^{-1}\left(\frac{P_L}{2f}\right) \quad (1)$$

where $\alpha_L = \alpha$ and $\alpha_R = -\alpha$ ($\alpha =$ projection angle, in general) are the left and right directional projection angles, respectively; P_L is the pitch of the elemental lens of the lens array; and f is the focal length of the lens array, which is also used as a gap ($g = f$) between the elemental image plane (the diffuser screen) and the lens array. Note that in the proposed method, only

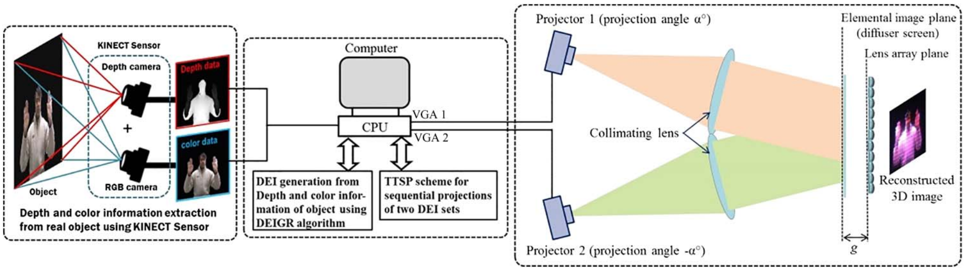


Fig. 2. Architecture of the proposed viewing-angle-enhanced integral imaging display (VAEIID) system.

horizontal directional projections are considered. In a similar way, a vertical directional projection scheme can be performed to enhance the vertical viewing angle of the II display system.

The viewing angle of the proposed VAEIID system can be calculated as

$$\theta_{\text{proposed}} = 2\tan^{-1}\left(\frac{P_L}{f}\right) \cong 2\theta_{\text{convensional}} \tag{2}$$

where the viewing angle of the conventional II system is

$$\theta_{\text{conventional}} = 2\tan^{-1}\left(\frac{P_L}{2f}\right). \tag{3}$$

The architecture of the proposed VAEIID system is shown in Fig. 2. The VAEIID system is implemented with three main steps: i) acquisition of depth and color information of a real object, ii) information processing and generation of two sets of DEIs using a DEIGR algorithm, and iii) the TTSP scheme for the two-directional sequential projections of two sets of DEIs. The specific functions of these three steps are as follows.

Step 1: The real object's depth and color red-green-blue (RGB) information are extracted through an acquisition process by using a Kinect sensor and the Open CL Library [21]. In this process, both the depth and RGB color information of each pixel of the real object are collected, which are to be used in the elemental image—generation process for creating two sets of DEIs in order to project them in two different directions using the TTSP scheme.

Step 2: Two sets of DEIs are generated from the extracted depth and color information of the real object by using a DEIGR algorithm [20]. The DEIRG algorithm is capable of generating different DEI sets in terms of predefined angular directions by synthesizing the extracted depth and color information of the real object. For the proposed method, the directional projection angles are determined by (1), which is explained in detail in Section 2.2.

Step 3: The two DEI sets are projected using a TTSP scheme onto the same projection screen in order to retrace them through the same lens array from two different directions in a time-multiplexed sequential manner. In the TTSP scheme, the two DEI sets can share the same projection screen as well as be retraced through the same lens array, avoiding elemental image overlap. The TTSP scheme is explained in detail in Section 2.4.

2.2. Two Sets of Directional Elemental Images Generation Using a DEIGR Algorithm

A DEIGR algorithm is used for generating two DEIs sets from the depth and color information of a real object extracted by using a Kinect sensor [21], in order to project them in two different directions. The DEIGR algorithm is capable of synthesizing the extracted depth and RGB color information of the real object with different angular perspectives. In the proposed VAEIID

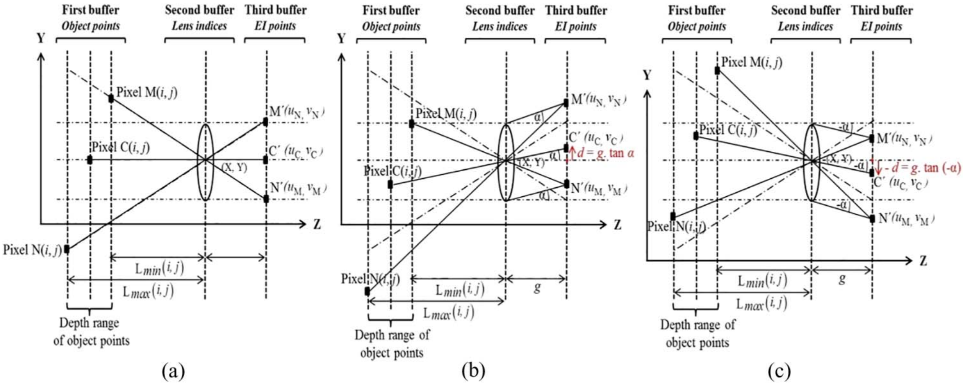


Fig. 3. Principle of pixel mapping for directional elemental image generation by using a DEIGR algorithm. (a) Pixel mapping for 0° (conventional), (b) pixel mapping for $\alpha_L = \alpha$, and (c) for $\alpha_R = -\alpha$ (proposed) directional projections with the optical axis off the lens array.

system, two sets of DEIs are generated by using the DEIGR algorithm to project them in two suitable angular directions predefined by the principle of the proposed method.

The principle of the DEIRG algorithm is illustrated in Fig. 3. Before generating the DEIs, the appropriate projection angles are first determined by using (1), depending on the parameters of the display components, such as elemental lens pitch (P_L), gap between the EI plane and the lens array ($g = f$), and the displacement of the PLS due to the directional projection (i.e., $d = (P_L/2)$), as shown in Fig. 1(a). Then, two DEI sets are generated by using the DEIGR algorithm, according to the two angular directions determined by (1). The DEIGR algorithm is based on a pixel mapping algorithm [21] and considering the directional projection geometry of each pixel for the object's planes, as well as the elemental image plane in terms of directional projection angle. In the proposed algorithm, each object point is mapped by following the principles depicted in Fig. 3, considering the projection geometry for each object pixel and elemental image pixel.

Moreover, after the pixel mapping process, an elemental image resizing function is applied in order to resolve the elemental image mismatch with the elemental lens pitch of the lens array, which occurs due to the directional projection geometry. The elemental image resizing functions are expressed as follows.

For a horizontal directional projection, the size of a directional elemental image in x and y axes can be calculated as

$$DEI_x(\text{hor}) = P_L\cos\alpha \text{ and } DEI_y(\text{hor}) = P_L. \tag{4}$$

On the other hand, for a vertical directional projection, the size of a directional elemental image in x and y axes can be calculated as

$$DEI_x(\text{ver}) = P_L \text{ and } DEI_y(\text{ver}) = P_L\cos\alpha. \tag{5}$$

A flow chart of the DEIGR algorithm is shown in Fig. 4. By using the DEIGR algorithm, the DEI sets can be generated for different directional projections (for example - 0°, 14°, and $-14°$), as shown in Fig. 5.

2.3. Design of the Optical Setup for the Proposed VAEIID System

To implement the proposed VAEIID system, it is important to design an optimal optical setup in order to adjust the two sets of DEIs projected by the two projectors onto a certain image space on the projection screen (i.e., the diffuser screen), according to the principle of the proposed method (see Fig. 1). The design of the optical setup of the VAEIID system is shown in Fig. 6.

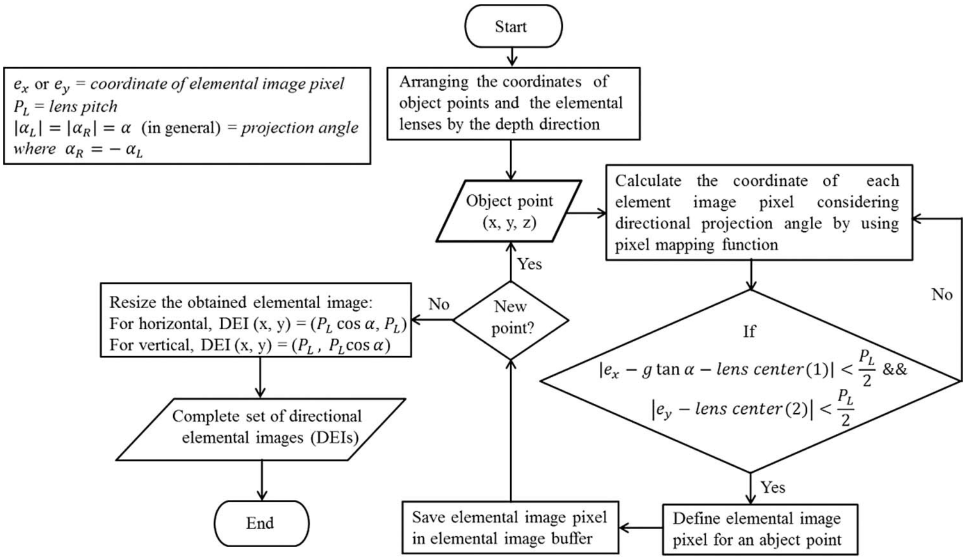
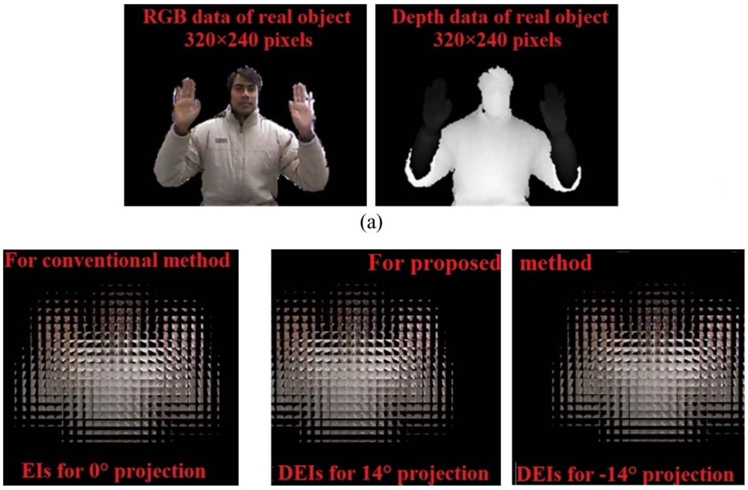


Fig. 4. Flow chart of the DEIGR algorithm.



(a)

(b)

(c)

Fig. 5. Generation of directional elemental image (DEI) sets using the DEIGR algorithm. (a) Depth and color (RGB) information of the real object, (b) generated EI set using the DEIGR algorithm for 0° projection (conventional), and (c) two sets of DEIs for $\alpha_L = 14^\circ$ and $\alpha_R = -14^\circ$ directional projections (the proposed method).

From Fig. 6, the distance between the collimating lens and the lens array plane can be determined with the following expression:

$$L = \frac{A}{2\tan\alpha} \tag{6}$$

where A is the aperture of the collimating lens, and α is the projection angle (in general).

Focusing distance of the projector (i.e., distance of diffuser screen) can be calculated as

$$F_{DP} = F_{CL} + L - \frac{g}{\cos\alpha} \tag{7}$$

where F_{CL} is the focal length of the collimating lens.

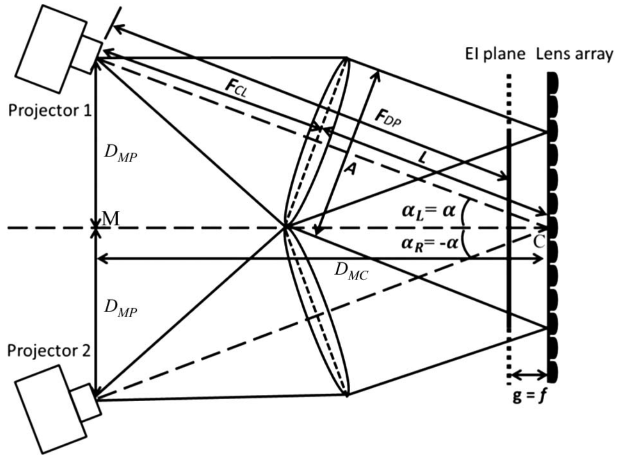


Fig. 6. Design of the optical setup for the proposed VAEIID system.

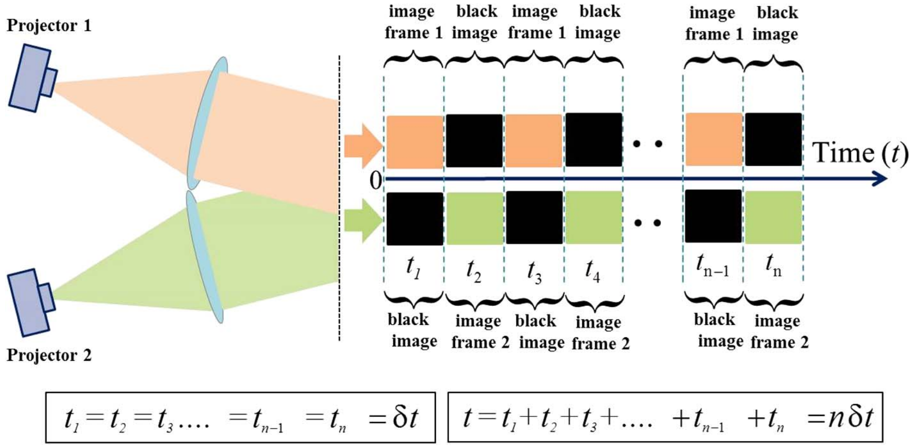


Fig. 7. Principle of the projection sequences of the TTSP scheme for a two-directional projection of two sets of DEIs.

The distance of each projector from the midpoint (M) of the two projectors is

$$D_{MP} = \left(F_{DP} + \frac{g}{\cos\alpha}\right)\sin\alpha \tag{8}$$

and the distance between the midpoint (M) of two projectors and the center (C) of the lens array is

$$D_{MC} = \left(F_{DP} + \frac{g}{\cos\alpha}\right)\cos\alpha = (F_{CL} + L)\cos\alpha. \tag{9}$$

2.4. Time-Multiplexed Two-Directional Sequential Projection (TTSP) Scheme

In the TTSP scheme, at first, three image frames—two image frames (namely, image frame 1 and image frame 2) for two DEI sets generated from the depth and color information of a real object by using the DEIGR algorithm and a black image (namely, image frame 0) with no information—are first created and loaded into the TTSP program. Second, sequential projection is performed in such a way that in the first sequence, image frame 1 is projected through projector 1 onto the elemental image plane (the diffuser screen) and, at the same time, image frame 0 is projected through projector 2 onto the same image screen (i.e., the diffuser screen) [see Fig. 2]. As a

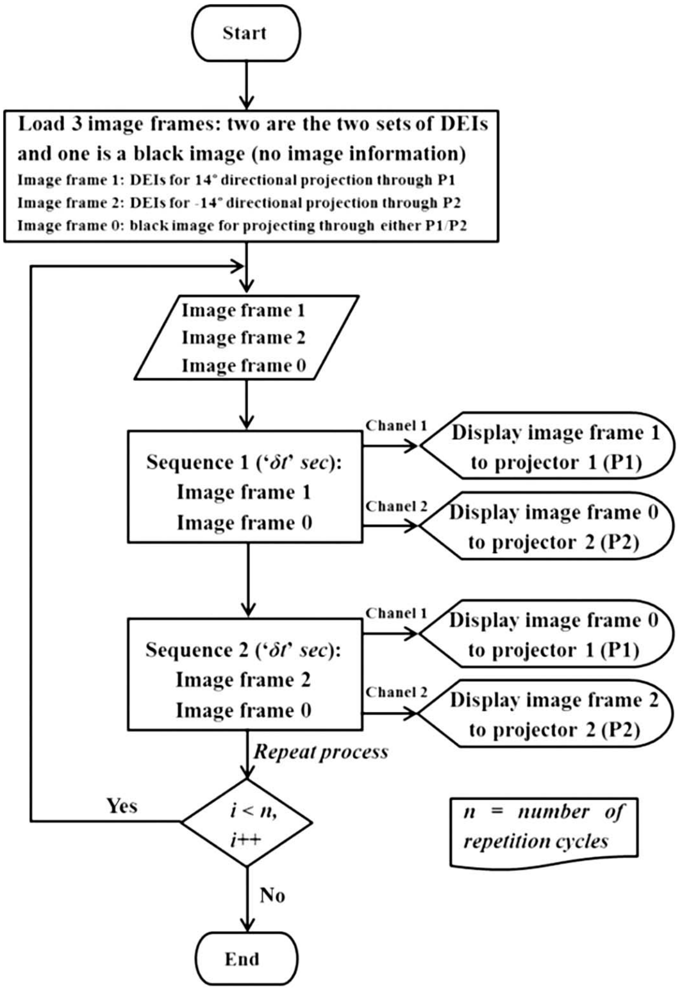


Fig. 8. Flow chart of the algorithm for the time-multiplexed two-directional sequential projection (TTSP) scheme.

result, on the elemental image screen, only image frame 1, consisting of the DEI set with projection angle α_L appears and continues to display until time interval δt. Then, in the second sequence, image frame 2 is projected through projector 2 onto the elemental image plane (the diffuser screen) and, at the same time, image frame 0 is projected through projector 1 onto the same the image screen.

As a result, on the elemental image screen, only image frame 2 consisting of the DEI set with projection angle α_R appears and continues to display until time interval δt. These two sequences are continued repeatedly in a time-multiplexed fashion with a uniform time interval of δt. The basic principle of the TTSP scheme is illustrated in Fig. 7. To implement the TTSP scheme, Microsoft Visual Studio and Open CV programs are used. The algorithm for the TTSP scheme is shown in a flow chart in Fig. 8.

3. Experimental Setup and Results

Fig. 9 shows the experimental setup of the proposed VAEIID system. To demonstrate the VAEIID system, a Kinect sensor (Model: Xbox 360) was used to capture a real object to extract the depth and color information of the object. To perform real object capture, as well as the depth and color information extraction processes, Microsoft Visual Studio 2010 and Open CL Library were used. After extraction of the real object's information, both the depth and RGB color

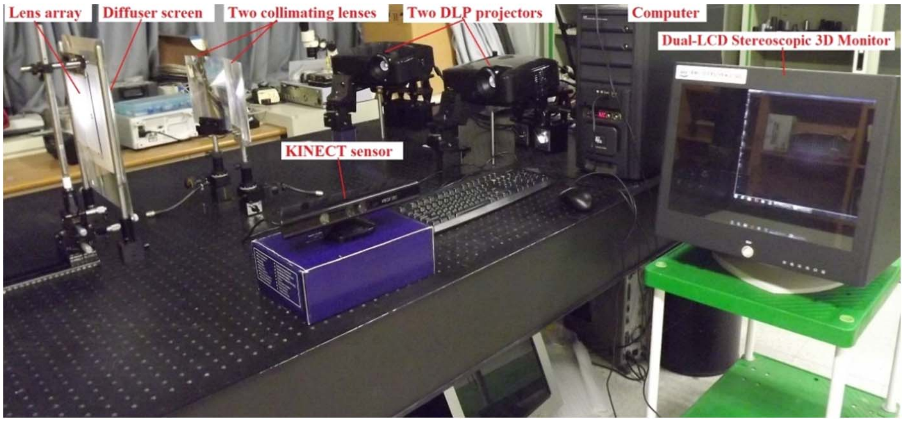
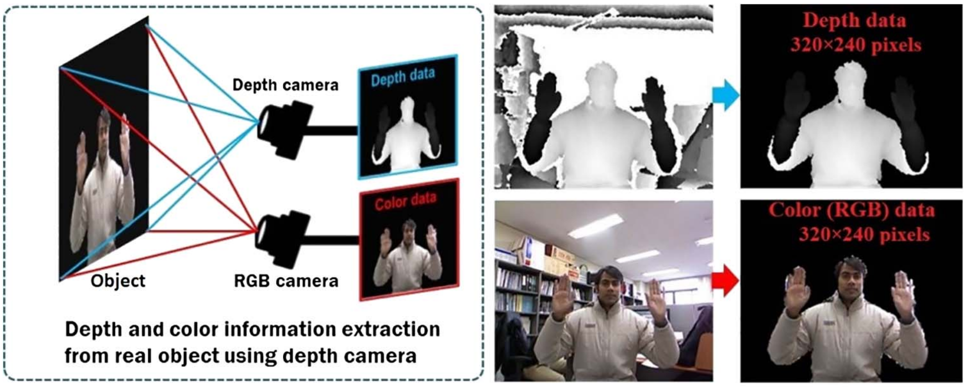


Fig. 9. Experimental setup of the proposed VAEIID system.



(a) (b)

Fig. 10. Real object capture. (a) Mechanism of depth and color information extraction using a Kinect sensor and (b) information processing for extraction of the region of interest (i.e., in between the depth ranges useful in integral imaging) from the whole image information captured by the Kinect sensor.

data were stored in the computer for use in the elemental image—generation process. The detectable depth range of the KINECT sensor (model: XBOX 360) used in the experiments is from 800 mm to 4000 mm. In the experiments, the depth range of captured 3-D screen was from 995 mm to 1207 mm, i.e., 212 mm.

From the extracted depth and color data of the real object, two sets of DEIs were generated by using the DEIGR algorithm with appropriate projection angles (i.e., 14° and -14°) as determined by (1). It can be noted that in the experiment, the depth and color information were captured by using a single Kinect sensor (i.e., captured with a 0° angle) and were used in the generation of two DEIs sets by synthesizing the extracted depth and RGB color data considering the perspectives of two predefined directional projection angles, instead of using two Kinect sensors for two-directional capture. It simplifies the capture process and avoids interference between infrared rays of two Kinect sensors operating at the same time from two different directions. The DEIGR algorithm successfully processed the depth data and the RGB data of the real object (extracted by using a single Kinect sensor) by synthesizing them according to directional angle to approximate the two different perspectives for the two sets of DEIs, because the directional angles were not very large (i.e., only 14° or -14°). Fig. 10 shows the extraction process of the depth and color (RGB) data of the real object.

Finally, the two sets of DEIs were projected onto the elemental image screen (the diffuser screen) in order to retrace them through the same area [see Fig. 1] of the lens array by using

TABLE 1

Key components of the proposed VAEIID system

Key components	Specifications	Characteristics
Lens array	Pitch of elemental lens	5 mm
	Focal length	10 mm
	Number of elemental lenses	30×30
Collimating lenses (2) [Fresnel lens]	Focal length	700 mm
	Aperture size (designed)	150mm×150mm
	Original aperture size	500mm×400mm
Kinect sensor	Model	XBOX 360
	Resolution of color information	320×240 pixels
	Resolution of depth information	320×240 pixels
Projectors (2)	Model	Optoma W2015
Dual-LCD stereoscopic 3D monitor (polarization-based)	LCD (2)	Samsung (Generic PnP Monitor)

TABLE 2

Design parameters of the VAEIID system

Parameters	Values
A	150 mm×150 mm
F_{CL}	700 mm
L	300.8 mm
F_{DP}	990.5 mm
D_{MP}	242 mm
D_{MC}	971 mm
α_L	14°
α_R	-14°
P_{pixel}	0.245 mm
δt	100 ~ 33 ms
fps	10 ~ 30

the TTSP scheme. To demonstrate this process, two DLP projectors (Model: Optoma W2015) were used with an appropriate optical setup (see Fig. 6) considering the projection geometry for the two directional projections according to the principle of the proposed method as shown in Fig. 1. To implement the TTSP scheme, Microsoft Visual Studio 2010 and Open CV programs were used for repeated time-multiplexed sequential projection of the two sets of DEIs.

In the experiment, we also used a dual-LCD stereoscopic (polarization-based) 3-D monitor to check the exact positioning and geometric matching of the two directional images projected through the designed VAEIID display system with the two directionally positioned DLP projectors in order for the projection images to meet in a common image space on the diffuser screen (as seen in Figs. 2, 6, and 9), according to the principle of the proposed method. The specifications of the key components are listed in Table 1. The important parameters for design and implementation of the proposed VAEIID system are shown in Table 2.

During the experiments, first of all, we determined the pixel pitch on the projection plane for a directionally (horizontal) projected image as a part of the calibration process [20]. The pixel pitch can be determined by using the following expression:

$$P_{pixel} = \frac{L_x \cos\alpha}{U_x} = \frac{L_y}{U_y} \tag{10}$$

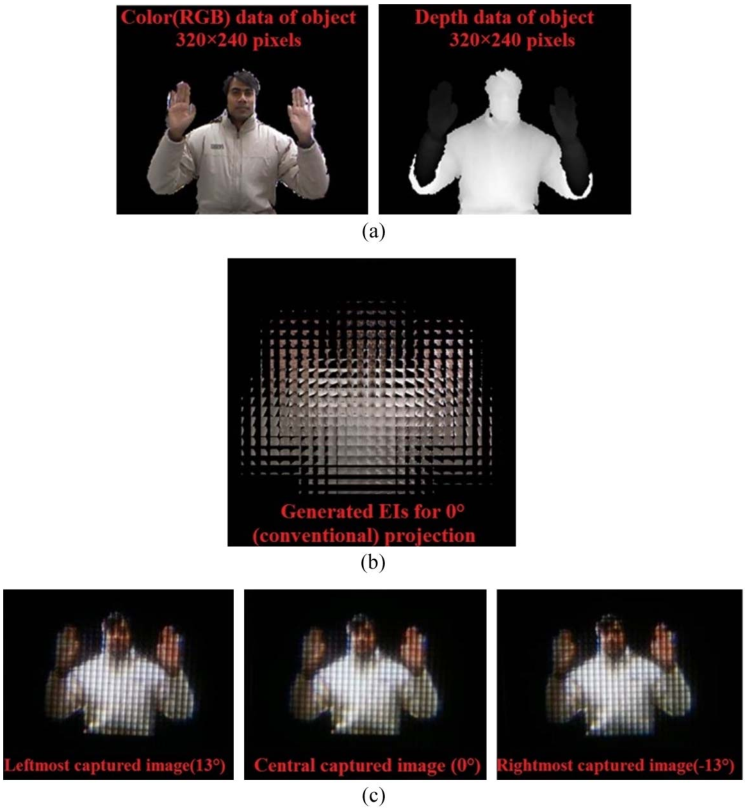


Fig. 11. Experimental results. (a) Depth and RGB color information of the real object, (b) generated elemental image (EI) set for 0° projections (using the conventional method) by using a DEIGR algorithm, and (c) reconstructed 3-D images from different viewing angles using 0° projections (with the conventional method).

where L_x and L_y are lengths of the test image on the projection screen on the x and y axes, respectively, and U_x and U_y are the number of pixels in one line of the test image along the x and y axes, respectively. In the experiment, the pixel pitch on the projection screen was determined by projecting a 400 × 400 test white image. The pixel pitch was determined to be 0.245 mm by using (10). Then the determined pixel pitch was used as an input parameter in the elemental image—generation program. Before starting the experiments, we also adjusted for suitable brightness, contrast, sharpness, etc., of the two DLP projectors.

By using the DEIGR algorithm in the elemental image generation for both the conventional II system and the proposed VAEIID system, the reconstructed 3-D images viewed from different positions are presented in Figs. 11 and 12, respectively. Fig. 11(a) shows the depth and color information of a real object, whereas Fig. 11(b) shows a DEI set with a 0° projection angle (for the conventional system) using the DEIGR algorithm, and Fig. 11(c) shows the leftmost, central and rightmost captured images. Fig. 12(a) shows the depth and color (RGB) information of the real object, Fig. 12(b) shows two sets of DEIs with 14° and -14° projection angles, respectively, (for the proposed system) using the DEIGR algorithm, and Fig. 12(c) shows the leftmost, central, and rightmost captured images. From Fig. 11(c), we can see that the total viewing angle for the conventional II system is 26° (i.e., $13^\circ + 13^\circ$), whereas Fig. 12(c) shows that the total viewing angle of the proposed VAEIID system is 50° (i.e., $25^\circ + 25^\circ$), which is enhanced by almost twice that of the conventional system (i.e., 26°). Hence, the proposed VAEIID system enhances the viewing angle by almost two times that of the conventional II system. Table 3 shows a comparison of the viewing angles between the conventional II system and the proposed VAEIID system.

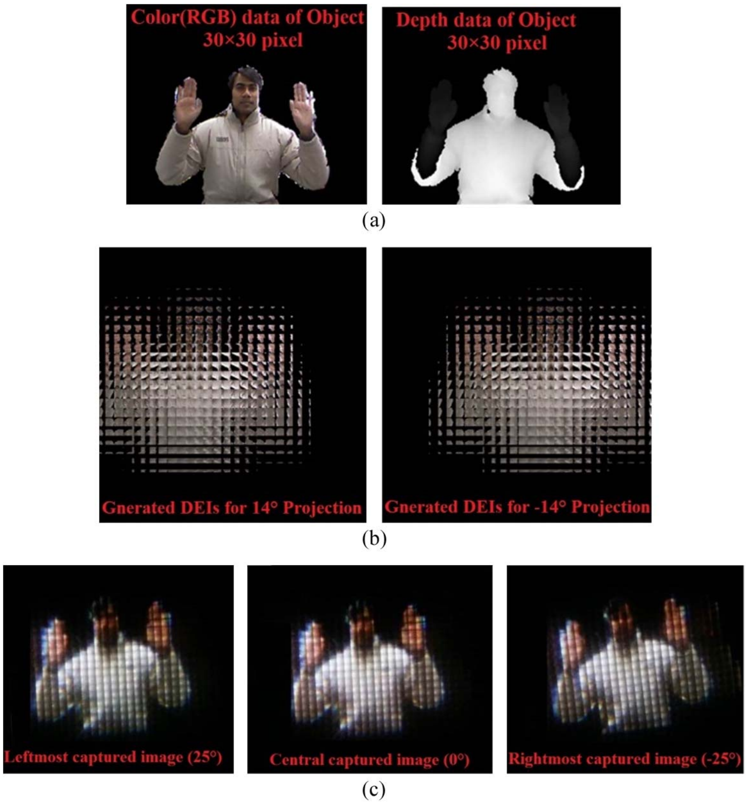


Fig. 12. Experimental results. (a) Depth and RGB color information of the real object, (b) generated directional elemental image (DEI) sets using the DEIGR algorithm for 14° and −14° directional projections, and (c) reconstructed 3-D images from different viewing angles using the proposed method (i.e., the viewing angle is enhanced by almost two times, compared to the conventional method).

TABLE 3

The experimental results in comparison with a conventional system

Experiments	**Leftmost viewing position**		**Central viewing position**		**Rightmost viewing position**		**Total viewing angle**	
	Cal.	**Exp.**	**Cal.**	**Exp.**	**Cal.**	**Exp.**	**Cal.**	**Exp.**
Conventional method (i.e. with single EI	-14.036°	-13°	0°	0°	14.036°	13°	28.072°	26°
Proposed method (i.e. with two DEI sets at -14°	-26.565°	-25°	0°	0°	26.565°	25°	53.13°	50°

In principle, ideally, there would not be any overlap between the two directional image sets, because in the TTSP (time-multiplexed two-directional sequential projection) scheme: when one projector (for example projector 1) projecting an elemental image set (i.e., image frame 1) at the same time another projector (i.e., projector 2) projects black image (i.e., image frame 0) that means no image information from the projector 2 appears on the projection screen (diffuser screen), so only image information from projector 1 will be displaying within a certain time interval (δt). Alternatively, in the next time interval, the image fame (i.e., image frame 2) from projector 2 will be appearing on the projection screen, while the projector 1 will project black image (no image information). In this case, no image overlapping occurs.

However, the integral imaging technique has an inherited problem that the pixel information of closer pixel from the neighboring elemental image flips by the neighboring elemental lenses. Our proposed system also experiences this kind of image flipping as we use diffuser screen, but it is a considerable range. If the two projection devices (DLP projectors) are replaced by a single LCD panel with two directional sequential backlight units, then this problem can be overcome or compensated effectively. Actually, in this study, to verify the principle of enlarging the viewing angle with two-directional time-multiplexed sequential projections scheme, two ordinary DLP projectors and a suitable diffuser screen are used. For a precise and commercial implementation, the system can be developed by replacing the two ordinary projection devices into an advance LCD or other display device using two-directional sequential backlighting units in a time sequential manner.

4. Conclusion

From this study, we conclude that the proposed VAEIID system using a TTSP scheme and a DEIGR algorithm enhances the viewing angle, compared to a conventional II system. The experimental results verified that the proposed method can enhance the viewing angle by almost two times [i.e., 50°; see Fig. 12(c)] that of the conventional system [i.e., 26°; see Fig. 11(c)]. A comparison of the viewing angles from experimental results with the conventional II system and the proposed VEAIID system is shown in Table 3. However, the quality of the reconstructed images is not very much impressive because of the limitation in the resolution of color and depth information of the Microsoft Kinect sensor (i.e., only 320 × 240 pixels). If high resolution color and depth information of real object are used, then the quality of the reconstructed images will improve. In experiments, we used the Kinect sensor for conforming possibility of implementation of a real-time VAEIID system in a further development. Furthermore, the proposed VAEIID system can be extended to a real-time system by using high-speed projection devices and graphics processing unit parallel processing.

References

[1] M. G. Lipmann, “Epreuves reversibles donnant la sensation du relief,” *J. de phys.*, vol. 7, no. 1, pp. 821–825, 1908.

[2] Y. Igarishi, H. Murata, and M. Ueda, “3-D display system using a computer generated integral photography,” *Jpn. J. Appl. Phys.*, vol. 17, no. 9, pp. 1683–1684, Sep. 1978.

[3] S. Jung, S.-W. Min, J.-H. Park, and B. Lee, “Study of three-dimensional display system based on computer-generated integral photography,” *J. Opt. Soc. Korea*, vol. 5, no. 2, pp. 43–48, Sep. 2001.

[4] J.-H. Park, S.-W. Min, S. Jung, and B. Lee, “Analysis of viewing parameters for two display methods based on integral photography,” *Appl. Opt.*, vol. 40, no. 29, pp. 5217–5232, Oct. 2001.

[5] Y. Kim *et al.*, “Point light source integral imaging with improved resolution and viewing angle by the use of electrically movable pinhole array,” *Opt. Exp.*, vol. 15, no. 26, pp. 18253–18267, Dec. 2007.

[6] J.-H. Park, J. Kim, Y. Kim, and B. Lee “Resolution-enhanced three-dimension/two-dimension convertible display based on integral imaging,” *Opt. Exp.*, vol. 13, no. 6, pp. 1875–1884, Mar. 2005.

[7] M. Yamasaki, H. Sakai, T. Koike, and M. Oikawa, “Full-parallax autostereoscopic display with scalable lateral resolution using overlaid multiple projection,” *J. Soc. Inf. Display*, vol. 18, no. 7, pp. 494–500, Jul. 2010.

[8] M. A. Alam, G. Baasantseren, M.-U. Erdenebat, N. Kim, and J.-H. Park, “Resolution enhancement of integral-imaging three-dimensional display using directional elemental image projection,” *J. Soc. Inf. Display*, vol. 20, no. 4, pp. 221–227, Apr. 2012.

[9] A. Stern and B. Javidi, “Three-dimensional image sensing and reconstruction with time-division multiplexed computational integral imaging,” *Appl. Opt.*, vol. 42, no. 35, pp. 7036–7042, Dec. 2003.

[10] J.-H. Park, K. Hong, and B. Lee, “Recent progress in three-dimensional information processing based on integral imaging,” *Appl. Opt.*, vol. 48, no. 34, pp. H77–H94, Dec. 2009.

[11] B. Lee, S. Jung, and J.-H. Park, “Viewing-angle-enhanced integral imaging by lens switching,” *Opt. Lett.*, vol. 27, no. 10, pp. 818–820, May 2002.

[12] Y. Kim *et al.*, “Wide-viewing-angle integral three-dimensional imaging system by curving a screen and a lens array,” *Appl. Opt.*, vol. 44, no. 4, pp. 546–552, Feb. 2005.

[13] J.-S. Jang and B. Javidi, “Improvement of viewing angle in integral imaging by use of moving lenslet arrays with low fill factor,” *Appl. Opt.*, vol. 42, no. 11, pp. 1996–2002, Apr. 2003.

[14] J.-S. Jang and B. Javidi, “Three-dimensional projection integral imaging using micro-convex-mirror arrays,” *Opt. Exp.*, vol. 12, no. 6, pp. 1077–1083, Mar. 2004.

[15] R. Martinez-Cuenca, H. Navarro, G. Saavedra, B. Javidi, and M. Martínez-Corral, “Enhanced viewing-angle integral imaging by multiple-axis telecentric relay system,” *Opt. Exp.*, vol. 15, no. 24, pp. 16 255–16 260, Nov. 2007.

[16] H. Choi, J.-H. Park, J. Kim, S.-W. Cho, and B. Lee, “Wide-viewing-angle 3-D/2-D convertible display system using two display devices and a lens array,” *Opt. Exp.*, vol. 13, no. 21, pp. 8424–8432, Oct. 2005.

[17] J.-H. Park, J. Kim, J.-P. Bae, Y. Kim and B. Lee, “Viewing angle enhancement of three-dimension/two-dimension convertible integral imaging display using double collimated or non-collimated illumination,” *Jpn. J. Appl. Phys.*, vol. 44, no. 31, pp. L991–L994, Jul. 2005.

[18] H. Choi, S.-W. Min, S. Jung, J.-H. Park, and B. Lee, “Multiple-viewing-zone integral imaging using a dynamic barrier array for three-dimensional displays,” *Opt. Exp.*, vol. 11, no. 8, pp. 927–932, Apr. 2003.

[19] G. Baasantseren, J.-H. Park, K.-C. Kwon, and N. Kim, “Viewing angle enhanced integral imaging display using two elemental image masks,” *Opt. Exp.*, vol. 17, no. 16, pp. 14405–14417, Aug. 2009.

[20] M. A. Alam, M.-L. Piao, L. T. Bang, and N. Kim, “Viewing-zone control of integral imaging display using a directional projection and elemental image resizing method,” *Appl. Opt.*, vol. 52, no. 28, pp. 6969–6978, Oct. 2013.

[21] G. Li *et al.*, “Simplified integral imaging pickup method for real objects using a depth camera,” *J. Opt. Soc. Korea*, vol. 16, no. 4, pp. 381–385, Dec. 2012.