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Three-dimensional reconstruction for a large scene of integral imaging based on color-position characteristics*

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A new large-scale three-dimensional (3D) reconstruction technology based on integral imaging with color-position characteristics is presented. The color of the object point is similar to those of corresponding points. The corresponding point coordinates form arithmetic progressions because integral imaging captures information with a senior array which has similar pitches on x and y directions. This regular relationship is used to determine the corresponding point parameters for reconstructing 3D information from divided elemental images separated by color, which contain several corresponding points. The feasibility of the proposed method is demonstrated through an optical indoor experiment. A large-scale application of the proposed method is illustrated by the experiment with a corner of our school as its object.

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Three-dimensional (3D) reconstruction has become popular recently, especially with the development of 3D printing technology. Optical 3D reconstruction technology can be categorized into structured light[1-5] and passive optical 3D reconstruction technologies[6,7]. The former is more developed for reconstructing an object illuminated by structured light. Structured light on a large-scale scene is limited by the structured light itself. The illuminating range limits the range of the 3D scene. Multi-viewpoint and integral imaging 3D reconstruction technologies are passive optical 3D reconstruction techniques that solve the problem of 3D scene range. 3D information is reconstructed from images through image registration. Numerous studies, such as 3D information reconstruction[8], self-screening[9], view analysis[10], real-time computer-generated technique[11], improved 3D image reconstruction by curved integral imaging[12,13] and super-resolution reconstruction technique[14], have been conducted to solve the registration problem. However, most of these studies are useful for small scenes only. The calculation time and registration become unacceptable for large-scale scenes.

In this paper, a new large-scale 3D reconstruction technology through integral imaging[8,9,15] with color-position characteristics is presented. Integral imaging captures 3D information with a lens array. The colors of corresponding O' points in elemental images are similar to those of object O. These point coordinates form arithmetic progressions, because the lens array is constructed with the similar pitches on x and y directions. The parameter colors and O' coordinates are related to those of the corresponding O' points. Elemental images are separated during reconstruction by the color used to simplify the next process. The divided elemental images have several corresponding points, but not all of these points are in the elemental images. The parameters of the corresponding O' points are obtained from the divided elemental images by arithmetic progression. Optical experiments are conducted to confirm our proposed method. An optical experiment with a small 3D scene in the laboratory is successfully performed to demonstrate the feasibility of our proposed method. An optical experiment with an outdoor 3D scene is performed to confirm the effectiveness of the proposed method for large-scale scenes.

3D information is captured by a lens array and recorded by elemental images in integral imaging. The principle is shown in Fig.1(a).

The object point $O(x_O, y_O, z_O, R_O, G_O, B_O)$ is captured by the lens array, where the object point O with color of R_O, G_O and B_O is at the position of (x_O, y_O, z_O). The lens array comprises a regular lens placed on the XOY plane as shown in Fig.1(b). $D_{(i,j)}$ is a lens in the lens array, which is the ith lens in the x direction and the jth lens in the y direction. The coordinates of $D_{(i,j)}$ are shown as

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$$D_{(i,j)}=\begin{cases}x_{D(i,j)}=x_{D(1,1)}+(i-1)\times p_x\\ y_{D(i,j)}=y_{D(1,1)}+(j-1)\times p_y\\ z_{D(i,j)}=0\end{cases}, \tag{1}$$

where $x_{D(i,j)}$ and $y_{D(i,j)}$ are the coordinates of $D_{(i,j)}$, and p_x and p_y are the pitches of the neighbor lens in the lens array on x and y directions, respectively. The elemental images are shown in Fig.1(c). $I_{(i,j)}$ is the elemental image which is captured by the lens $D_{(i,j)}$. Thus, $O'_{(i,j)}$ is the image of O captured by $D_{(i,j)}$, which has the coordinates of

$$\begin{cases}x_{O'(i,j)}=\beta\times(x_O-x_{D(i,j)})+x_{D(i,j)}\\ y_{O'(i,j)}=\beta\times(y_O-y_{D(i,j)})+y_{D(i,j)}\\ \beta=g/a\end{cases}, \tag{2}$$

where g is the distance between the elemental image plane and lens array plane, and a is the distance between O and the lens array plane which is the same as z_O in this condition. Substituting Eq.(1) into Eq.(2), it can be obtained that

$$\begin{cases}x_{O'(i,j)}=\left[\beta\times x_O+(1-\beta)x_{D(1,1)}\right]+(i-1)\times\left[(1-\beta)p_x\right]\\ y_{O'(i,j)}=\left[\beta\times y_O+(1-\beta)y_{D(1,1)}\right]+(j-1)\times\left[(1-\beta)p_y\right]\end{cases}. \tag{3}$$

Eq.(3) shows that the coordinates of O' in the elemental images form a two-dimensional arithmetic progression as shown in Fig.1(c). The set of O' is called the corresponding O' points, determined by (a_{1x}, a_{1y}, d_x, d_y, R, G, B), which can be expressed as

$$\begin{cases}a_{1x}=\beta\times x_O+(1-\beta)\times x_{D(1,1)}\\ a_{1y}=\beta\times y_O+(1-\beta)\times y_{D(1,1)}\\ d_x=(1-\beta)\times p_x\\ d_y=(1-\beta)\times p_y\\ x_{O'(i,j)}=a_{1x}+(i-1)\times d_x\\ y_{O'(i,j)}=a_{1y}+(j-1)\times d_y\end{cases}, \tag{4}$$

which shows that the coordinates of the corresponding O' points are regulated as arithmetic progressions. The first terms in x and y coordinates are a_{1x} and a_{1y}, and the common differences in x and y coordinates are d_x and d_y, respectively. The parameters of an integral imaging system, such as g, p_x, p_y and $D_{(1,1)}$, are known. $O'(a_{1x}, a_{1y}, d_x, d_y, R, G, B)$ only depends on $O(x_O, y_O, z_O, R_O, G_O, B_O)$. These values have a one-to-one correspondence.

Elemental images are the set of O' which is imaged by the lens array. If $O'(a_{1x}, a_{1y}, d_x, d_y, R, G, B)$ can be separated from the elemental images, the object point O can be calculated by O'.

A set of many corresponding points should be separated individually in elemental images. First, the elemental images are separated by color (R, G, B) because the corresponding O' points have the same colors as O as shown in Fig.2. The separated elemental images which have the same color (R, G, B) contain only several corresponding points with the same color of (R, G, B) and different parameters of a_{1x}, a_{1y}, d_x and d_y. These parameters can be obtained from the separated elemental images shown in Fig.3. The object point O can be calculated by

$$x_O=\frac{a_{1x}-\frac{d_x}{p_x}\times x_{D(1,1)}}{1-\frac{d_x}{p_x}},$$

$$y_O=\frac{a_{1y}-\frac{d_y}{p_y}\times y_{D(1,1)}}{1-\frac{d_y}{p_y}},$$

$$z_O=\frac{g}{1-\frac{d_y}{p_y}}. \tag{5}$$

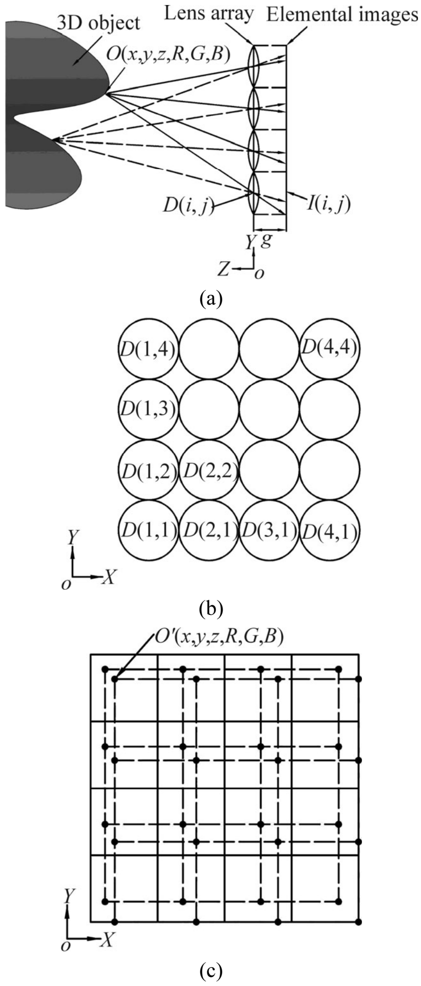


Fig.1 (a) Optical path of integral imaging; (b) Sketch map of lens array; (c) Sketch map of elemental images

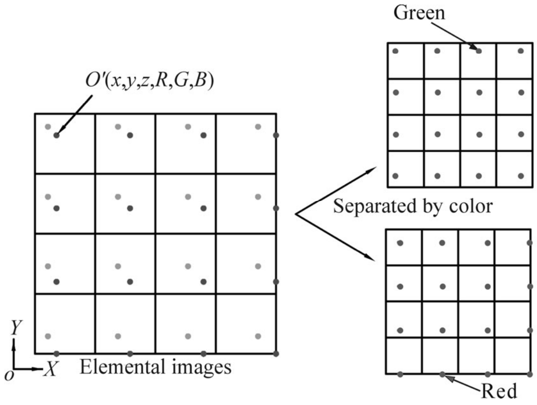


Fig.2 Principle of integral imaging

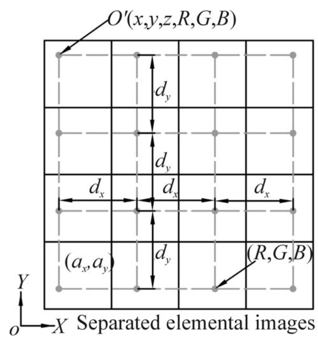


Fig.3 Schematic diagram of separated elemental images

Optical experiments are performed to validate the proposed method. An optical experiment is conducted in the laboratory as shown in Fig.4, and the parameters are listed in Tab.1.

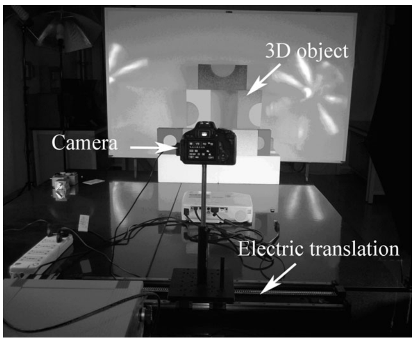


Fig.4 Picture of the integral imaging pick-up system

Tab.1 Parameters of the integral imaging pick-up system

Parameter	Value
p_x	20 mm
p_y	0 mm
g	50 mm
Coordinates of $D_{(1,1)}$	(0, 0)
Size of camera array	16×1

The elemental images captured by the integral imaging system are shown in Fig.5. One of the elemental images separated by color and formatted into a binary image for the next calculation is shown in Fig.6.

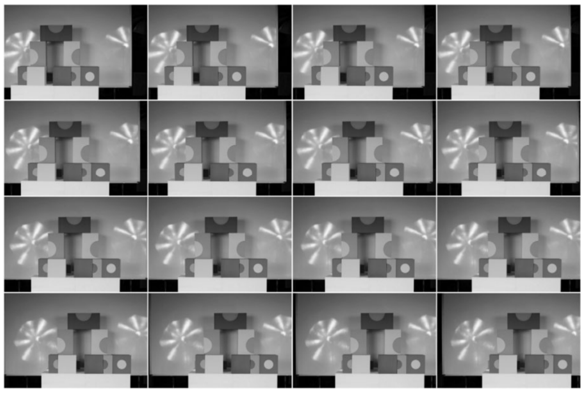


Fig.5 Elemental images captured by integral imaging system

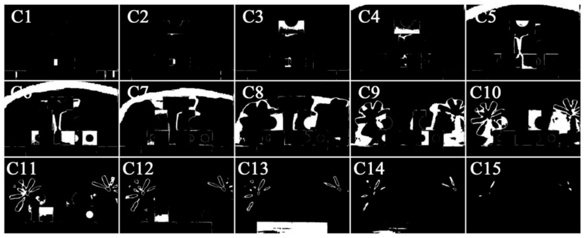
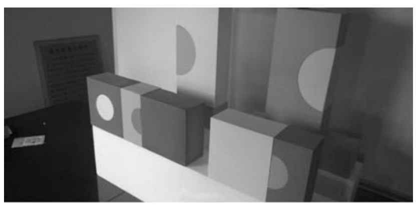


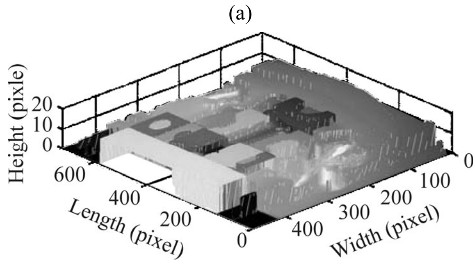
Fig.6 Elemental images separated by color

All elemental images are separated by color. The set of separated elemental images with similar colors is then used to obtain a_{1x} and a_{1y}. The reconstructed 3D information is shown in Fig.7.

The 3D object shown in Fig.7(a) is built using several toy blocks with different colors. The reconstructed 3D object is shown in Fig.7(b). The proposed integral imaging 3D information measurement with color-position characteristics can reconstruct the 3D object successfully. More details are shown in Fig.7(c) and (d). Fig.7(c) shows that the toy blocks with the same color and placed in different layers with different z coordinates are reconstructed successfully. Fig.7(d) shows that the toy blocks with different colors and placed in the same layer with the same z coordinate are also reconstructed successfully.



(a)



(b)

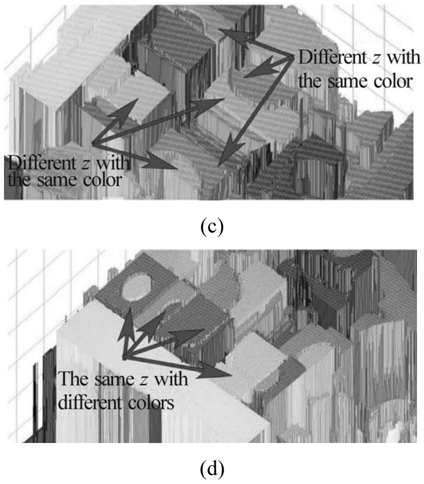


Fig.7 3D object and reconstructed 3D image: (a) 3D object; (b) Reconstructed 3D image; (c) Reconstructed 3D object on different *z* with the same color; (d) Reconstructed 3D object on the same *z* with different colors

A second outdoor optical experiment is performed, and the parameters are shown in Tab.2. The scene is a corner of our campus (N36°34′8.00″, E114°29′24.12″). The satellite map of this corner is shown in Fig.9(a) from BaiduMap. The camera is held by a tripod, and the camera array is manipulated by moving the tripod with the same distance of p_x.

Tab.2 Parameters of the outdoor integral imaging pick-up system

Parameter	Value
p_x	600 mm
p_y	0 mm
g	50 mm
Coordinates of $D_{(1,1)}$	(0, 0)
Size of camera array	21×1

The elemental images captured by the outdoor integral imaging system are shown in Fig.8, and the reconstructed 3D object results are shown in Fig.9(b)–(d).

Fig.8 Elemental images captured by the outdoor integral imaging system

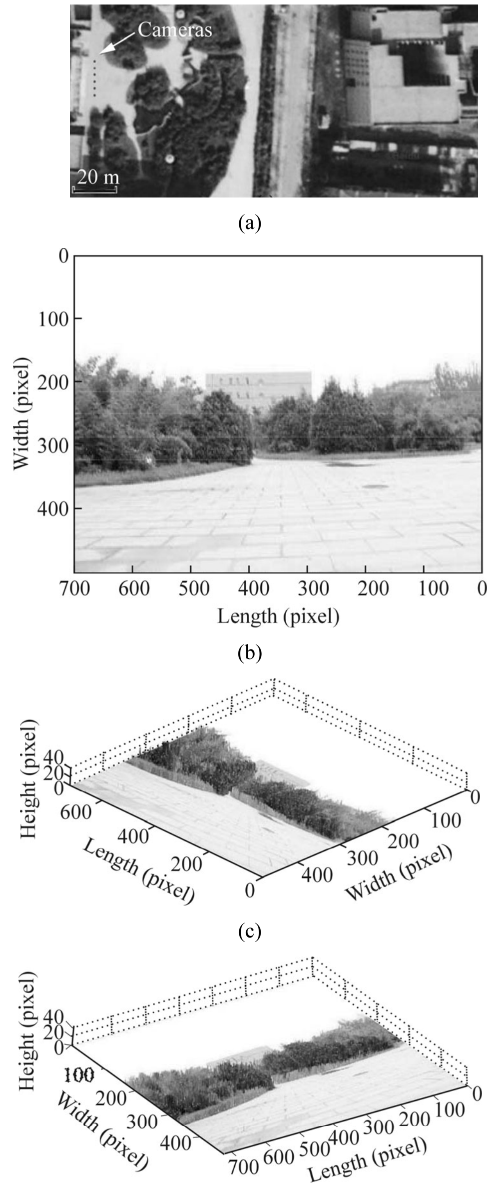


Fig.9 (a) Satellite map of the corner of our campus, and (b) middle, (c) left, and (d) right viewing points of the reconstructed image

This paper presents a new large-scale 3D information measurement technology through integral imaging based on color-position characteristics. Integral imaging can be used to capture information by means of a lens array with similar pitches on x and y directions. 3D information is captured by the lens array and recorded on the elemental images. Each object point imaged by the lens array has its unique color-position characteristics. The elemental images are separated by color. This separation is used to reduce the distraction and simplify the next process. The parameters of the corresponding points (a_{1x}, a_{1y}, d_x, d_y, R, G, B) are obtained from the separated elemental images. The parameters of the 3D object point (x_O, y_O, z_O, R_O, G_O, B_O) can be calculated with the corresponding point parameters. An indoor optical experiment is conducted to demonstrate the feasibility of the proposed method. The 3D information of the 3D object composed of toy blocks with different colors is obtained with the proposed method. An outdoor optical experiment is performed to illustrate the large-scale application of the proposed method. The 3D information of a corner of our campus is also captured by the proposed method.

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