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Three-dimensional object rotation-tolerant recognition for integral imaging using synthetic discriminant function

Jinbo Hao, Xiaorui Wang*, Jianqi Zhang, Yin Xu

School of Technical Physics, Xidian University, Xi'an Shaanxi 710071, China

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ABSTRACT

This paper presents a novel approach of three-dimensional object rotation-tolerant recognition that combines the merits of Integral Imaging (II) and Synthetic Discriminant Function (SDF). SDF aims at filters and distortion-tolerant recognition, and we use it for three-dimensional (3-D) rotation-tolerant recognition with II system. Using high relevancy of elemental images of II, the approach can not only realize 3-D rotation-tolerant recognition, but also reduce computational complexity. The correctness has been validated by experimental results.

1. Introduction

3-D object recognition has been the subject of much interest in recent years and it can provide the benefit of depth of information of 3-D objects in comparison with 2-D imaging information techniques. Integral imaging (II) has been the most interesting 3-D imaging technique for its simplicity [1–3]. A number of new applications, such as 3-D object recognition and 3D object reconstruction have been introduced [4–10]. II system can reduce overlapping of images and debase eye fatigue of observers, and unlike holographic techniques, II systems can work with incoherent light.

In II system, the information of 3-D objects is acquired by using an array of microlens to form a set of 2-D perspective elemental images array onto a CCD. These images are known as elemental images since each one consists of a different depth informant of 3-D object, and every single one projects a different angle to 3-D objects, and so the depth informant is relative to the angle information. This characteristic of microlens array is called angle-depth conversion.

For more practical applications, 3-D objects rotation-tolerant recognition for integral imaging has been widely investigated using different approaches [11–14], but many approaches not only need much calculation, but they also fail to realize complete rotation-tolerant recognition. Synthetic Discriminant Function (SDF) was proposed for filters, and it is used in rotation-tolerant recognition systems widely [15–17]. Its intention is to find a filter function that can obtain the same correlation outputs if rotational objects were inputted. But general SDF needs more samples to compose the training set, which results in greater computational complexity and lower practicability. Meanwhile, high relevancy of perspective elemental images array of II system can eliminate the above shortcoming of SDF. So connecting with II system, SDF can be used for 3-D rotation-tolerant recognition as a novel approach. By the use of high relevancy of perspective elemental images array, SDF can not only realize rotation-tolerant recognition, but also reduce computational complexity, and more importantly, precision of recognition is high.

In this paper, a novel approach of 3-D object rotation-tolerant recognition for integral imaging using SDF is presented. By using perspective elemental images array to synthesize the SDF and simulating optically matched filtering process, 3-D object rotation-tolerant recognition is realized. In comparison with other approaches, the proposed system can greatly reduce computational complexity and enhance the recognition efficiency. The result also shows robustness and stability of the proposed system. The correctness has been validated by experimental results.

2. Theoretical analysis of rotation-tolerant recognition

The principle of 3-D object rotation-tolerant recognition using II system is shown in Fig. 1. Parameter a is the object distance, and b and M are the focal length and magnification of microlens, respectively. $\varDelta$ is the cycle of microlens array, and $M\varDelta$ and $2M\varDelta$ are spatial displacements. Rotational angle θ is calculated by

$$\tan\theta = \frac{\varDelta}{a} \tag{1}$$

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* Corresponding author.
E-mail addresses: haojinbo@sina.com (J. Hao), xrwang@mail.xidian.edu.cn (X. Wang).

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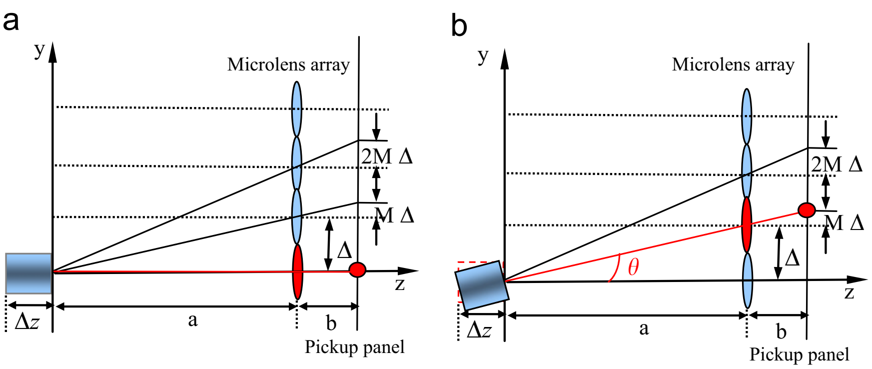

Fig. 1. Projection of 3-D input into elemental images: (a) imaging of 3-D object with microlens array, and (b) imaging of rotational 3-D object. Only two dimensions are considered in the figure. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

where we have assumed $\Delta z \ll a$. Because of the characteristic of II system, the rotational angle θ of a 3-D object must match the cycle of microlens array, and so angles are some discrete values. The minimum angle is also limited by the distance of the microlens array from the 3-D object. The distance in our experimental setup is 80 mm, the cycle of microlens array is 1 mm, and the minimum rotational angle is only 0.32°. If we increase the distance or have another microlens array whose cycle is much smaller (some microlens arrays are only 150 μm), the minimum angle can be much smaller, and the rotational angles would be seen as continuous values approximately.

The red microlens faces a face of the input 3-D object in Fig. 1(a). If the 3-D object is rotated at an angle θ, the adjacent microlens, the red microlens in Fig. 1(b), faces the same face of the input 3-D object. Thus the rotation of the 3-D object results only in the spatial shift of the elemental images, so that they can provide the same perspective elemental images with only a little shift of location in the pickup plane, and the shift distance is $\Delta+M\Delta$. Other elemental images are similar to that of the red microlens, and spatial displacement for each of the other microlenses is

$$s=\Delta+M\Delta \tag{2}$$

When the 3D object is rotated, though the adjacent lens is oblique capturing, the distortion should be ignored because of the small cycle of microlens array [1,13], and it has been already validated by experimental results. So rotational perspective elemental images and initial ones have high relevancy, and the rotation of the 3-D object can be easily recognized by the proposed operation as was shown.

The intention of seeking SDF is to find a filter function that can obtain same correlation output if rotational 3-D objects were inputted. Firstly, a training set is determined including many reference elemental images arrays that have different rotational angles. Secondly, the linear combination for the set is carried out to obtain a filter function. Thirdly, rotation-tolerant recognition is performed using the function.

The filter function h is the linear combination for the training set f_n, which is given by

$$h=\sum_{m=1}^{N} a_m f_m \tag{3}$$

where N is the number of reference elemental images arrays, and a is the weight factor.

The value of correlation output can be obtained by h and any image in f_n, and it is assumed as 1.

$$f_n \otimes h=1 \tag{4}$$

Instead of the spatial relationship of $f_n$and h, the value of correlation output is important, so Eq. (4) can be rewritten as

$$f_n \otimes h=f_n h=f_n \sum_{m=1}^{N} a_m f_m=\sum_{m=1}^{N} a_m r_{nm}=1 \tag{5}$$

where $r_{nm}=f_n f_m$, which denotes the elements of R, and R is the intersecting matrix of f_n.

Eq. (5) can be given as matrix form

$$Ra=(1,1,\cdots,1)^T=\mu \tag{6}$$

where μ denotes the unit vector.

Left multiplication is carried out on Eq. (6)

$$a=R^{-1}\mu \tag{7}$$

where R^{-1} denotes the inverse matrix of R.

We can obtain the filter function h after R^{-1} is obtained.

3. Recognition experimental implementation

In our experiment, the SDF is synthesized by simulating the optically matched filtering process. The elemental images are recorded by CCD, and Fourier transform is carried out to obtain the spectrum$F_i$of the images first, and then inverse Fourier transform for them is operated to obtain $f_i \otimes f_j$. Elements of the intersecting matrix r_{ij} are obtained through the value of correlation operations, and all r_{ij} values are synthesized to obtain the intersecting matrix R. The weight factor a can be obtained through the inverse operation of R. Finally, filter function h is obtained through the value of

$$h=\sum_{m=1}^{N} a_m f_m \tag{8}$$

where N is the number of reference elemental images arrays (N=24), and a is the weight factor (a=1).

In our experimental system, the rotation of 3-D object is controlled by an electrical three-dimensional rotating stage, and the precision of the stepping motor is 0.01°. The 3-D objects are two dice, with size 10 mm × 10 mm × 10 mm, which are used as target and reference object, and they are illuminated by a sodium lamp. The size of microlens array is 6 cm × 5 cm, and it is composed of 3000 periodic self-focusing lenses with 1 mm focal length and 1 mm period. The perspective elemental images arrays are recorded by CCD, and the size of pels is 8.6 μm × 8.3 μm. The device is shown in Fig. 2.

The target elemental image arrays and reference elemental image arrays are all 21 × 15 arrays. The elemental array of 2–3 faces of the reference 3-D object is as shown in Fig. 3(a), and Fig. 3b and c shows enlarged images of the left and right regions of