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# Structural design and image processing of a spherical artificial compound eye

Axiu Cao[a], Lifang Shi[a,*], Qiling Deng[a], Hui Pang[a], Man Zhang[a], Chunlei Du[b]

[a] *Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209, China*
[b] *Chongqing Institute of Green and Intelligent Technology, Chinese Academy of Sciences, Chongqing 401122, China*

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ABSTRACT

This manuscript presents a design method and corresponding image processing algorithms of a spherical artificial compound eye. The artificial compound eye is composed of multi-dimensional sub-eye imaging channels pointing to different directions. By using the principle of geometrical optics and imaging optics, the design method of the multi-dimensional imaging structure was analyzed. To satisfy the practical requirement of the structure, the image processing algorithm based on the segmentation rotation projection technology was studied. In order to validate the above design method and image processing algorithm, a spherical compound eye consisting of 37 imaging channels was fabricated and the corresponding imaging experiments were carried out. The results show that the field of view (FOV) of the imaging structure is up to 118° and the structure meets the practical requirements.



## 1. Introduction

With the optical imaging system widely applied in the field of biology, industry and national defense [1–4], the requirement of the performance of the system becomes more and more high. Wherein, the FOV which serves as an important parameter of the optical detection system needs to be improved urgently. Complex hybrid reflective/diffractive system constructed by a variety of optical glass materials of non-spherical structure is used in the traditional single channel imaging structure to extend the FOV [5]. These optical materials are not only expensive, but the processing method is very difficult. Also, the secondary spectrum which restricts the imaging quality of the imaging structure is difficult to be corrected. Therefore, the traditional imaging structure is difficult to satisfy the large FOV requirement. How to use a new type of imaging structure to get a breakthrough in the FOV is becoming a focus for researchers.

The compound eyes of insects are composed of small eyes from dozens to thousands pointing to different orientations [6,7]. Take advantage of the compound eye structure with a large number of small eyes, the large FOV detection can be realized. Inspired by the compound eyes of insects, scientists have presented different artificial compound eye imaging system [8–11]. To form a multi-channel image acquisition system, array of sub-eye lenses are used to simulate the small eyes of insects to realize a large FOV imaging.

In recent years, many research groups have carried out studies of the compound eye structure [12–15]. For achieving a large FOV detection, a lot of related works have been carried out. Biologically inspired artificial compound eyes [16] and digital cameras with designs inspired by the arthropod eye [17] have effectively reduced the weight and volume of the spherical imaging structure, however it is difficult for the structure to achieve the strict and precise control of the surface shape of the micro-lenses in the preparation process, so it is hard for practical use. The stereo omnidirectional imaging system (SOS) [18,19] has successfully taken all directional views and depth maps, but the key study of these works is dedicated to the analysis of depth images rather than the panoramic image. The PANOPTIC Camera [20] has presented a practical compound eye structure, but the arrangement of the sub-eye lenses can be improved and optimized for the full utilization of the visual field space.

In recent years, our group has carried out corresponding researches about the compound eye. The results of the design and formulation were proposed and published [8,21,22]. After that, to improve a practical spherical compound eye imaging structure with large FOV and high resolution over the whole field, further researches about design method, fabrication technology, and the corresponding image processing algorithm have been carried out in this manuscript. A criterion about the compound eye construction will be discussed in this manuscript. The validation

* Corresponding author.
*E-mail address:* shilifang@ioe.ac.cn (L. Shi).

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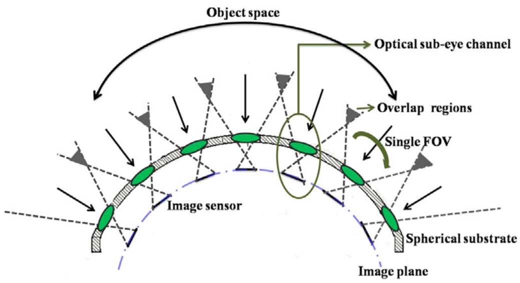


**Fig. 1.** The imaging principle of the compound eye.

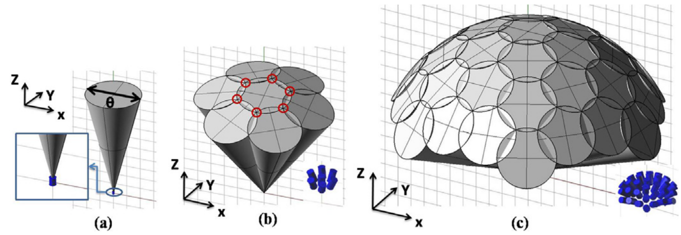

**Fig. 2.** The relationship between the arrangement of the lenses and the FOV distribution: (a) the single FOV of the lens, (b) the FOV of the 7 lenses, (c) the FOV situation of the designed compound eye with 37 lenses. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

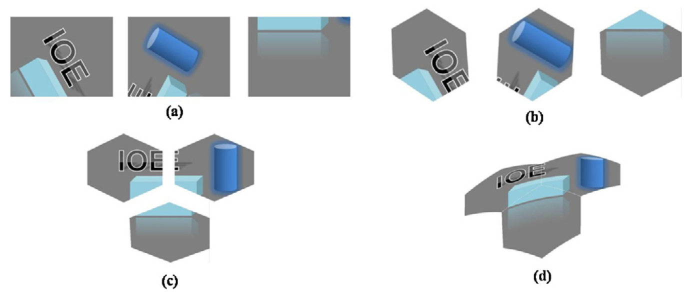

**Fig. 3.** The schematic diagram of the procedure of the image processing algorithm: (a) the original sub-images, (b) the sub-images after segmentation, (c) the sub-images after rotation, (d) the sub-images after projection.

experiments have been carried out to indicate that the artificial spherical compound eye structure fabricated by the design method can realize a large FOV of 118° detection based on the presented image processing algorithm. Consequently, the research has further improved the practical use of the artificial spherical compound eye.

## 2. Imaging principle of the artificial compound eye

The imaging principle of the compound eye imaging system is shown in Fig. 1. The system is composed of multiple independent optical sub-eye channels which are arranged on a spherical substrate. Each channel contains a sub-eye lens and an image sensor. The object located in the FOV of the channel can be imaged by the sub-eye lens and captured by the corresponding image sensor to form a sub-image. All the sub-images captured by all sensors can combine with each other to form a full image with large field of detecting space. The overlap regions exist among the adjacent channels for no dead zone detection. In the imaging structure, how to arrange the optical sub-eye channels and how to process the captured sub-images to form a full view image are the two key techniques which will be described in detail in the following parts.

## 3. Design and algorithm

Because array of sub-eye lenses are arranged on a spherical surface in the artificial compound eye structure, the key influence parameters need to be considered during the design of compound eye such as the arrangement of sub-eye lenses, the single FOVs of lenses, the whole FOV of the structure and so on. Therefore, high demands exist for the design method because so many parameters have great influence on the imaging effect of the compound eye structure. Meanwhile, due to the multi-channel array arrangement features of the artificial compound eye structure, a lot of corresponding captured sub-images need to be processed. The spatial transformation of the image is involved in during the image processing procedure, so it also presents high demands for the image processing algorithm to realize the image stitching of all sub-images.

### 3.1. Design of the compound eye structure

In the design of an artificial compound eye structure, the arrangement of the sub-eye channels containing the position of each sub-eye lens plays a critical role which relates to the final distribution of the FOV. While the arrangement of the sub-eye lens determines the final FOV, the arrangement of the FOV can represent the sub-eye lens arrangement according to the principle of imaging optics. Therefore, it is possible to use the distribution of the FOV to determine the coordinates of the lenses. Fig. 2(a) shows the FOV of a single lens according to the principle of geometrical optics, where the cone shows the FOV of $\theta$ and the zoomed in figure shows the lens in blue box. During the design of the compound eye, such as 7 lenses as shown in Fig. 2(b), the adjacent FOVs of lenses should be intersected at one point as more as possible (as shown in the red circle) for the full utilization of the visual field space by the arrangement techniques, where the rotation and array techniques are used to arrange 6 lenses around the central lens among the angle of 360° in turn. According to the above principle, the algorithm will be firstly programmed to calculate the position of the FOV of each lens, and then the arrangement radius ($R$) is determined by the relationship between images and objects. According to the above criterion, a compound eye with 37 imaging channels can be designed. Fig. 2(c) shows the FOV distribution by cones and the corresponding lens arrangement by blue boxes.

### 3.2. Image processing algorithm-segmentation rotation projection technology

After design of the artificial compound eye, the captured sub-images should be processed to obtain a full view. Accord with the arrangement parameters of the lenses in the above structural design, the distribution characteristics of the corresponding sub-images can be obtained by using imaging optics theory. According to the overlap situation of the entire FOV of the compound eye, the geometrical shape and spatial positions of the sub-images will be achieved. Subsequently, the image processing algorithm called segmentation rotation projection technology is presented to achieve a large FOV detection which can be described in the following three steps: (1) Segmentation. Since overlap regions exist among the adjacent imaging channels to realize a no dead zone detection, the redundant portions exist among the sub-images should be segmented. Fig. 3(a) shows the sub-images captured by sensors and Fig. 3(b) shows the sub-images after segmentation. (2) Rotation. Since the lens are arranged pointing to different directions, the sub-images should be rotated by certain angles according to the arrangement of the lenses for the later fitting together as shown in Fig. 3(c). (3) Projection. Since the lenses are arranged on a spherical surface, the sub-images should be projected onto a corresponding