Design of large field of view curved optical system based on ZEMAX

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Abstract. Structural design solved the problem in the paper that the large field of view and high resolution of the compound eye optical system can not be realized simultaneously. A curved compound eye system including a 3-ring lens group is designed. The compound eye system is divided into two parts: the central sub-eye system and the edge sub-eye system. The edge sub-eye system reduced the complexity of processing because of the same lens group. In the design process, we systematically studied the field of view between the single sub-eye system and the compound eye system, and obtained the arrangement of the sub-eyes. Then, the geometrical model of a single sub-eye system stitching is presented which is based on the conjugate relations between the incident and exit window. The whole field of the compound eye system designed by this method could reach up 79.5°, the angular resolution of the center system is 0.01°, and the angular resolution of the edge system is 0.017°. Compared with traditional single aperture optical system, the image quality of edge field of view is greatly improved, and the ability to acquire the target orientation is improved. Finally, the correctness of the optical system is validated with the optical design software ZEMAX. And this research could further promote the application of compound eye imaging system.

1. Introduction

With the development of high-tech into the direction of integration and miniaturization, the existing traditional monocular optical system can not meet the practical needs of people due to many factors, especially in the field of target recognition, positioning, tracking and other issues. For example, the contradiction between large field of view and high resolution [1]. The comparison of the resolution between compound eye and single eye is shown in Fig.1, where the yellow portion is the shared value portion.
In recent years, biologists have found that insect compound eyes had the characteristics of high sensitivity, small size, large field of view and sensitivity to moving targets. After that, the researchers made a deep research on the bionic compound eye theory. At present, many foreign research groups have proposed a number of bionic compound eye systems which was based on micro-lens array. The Japanese Tanida team has prepared the classic compound eye system TOMBO [2-4]. The German research team proposed an APCO similar to the TOMBO layer, which was based on the Bionic compound eye structure [5-11]. However, the image field of these planar compound eye structures is poor in image quality and the field of view is small, so it is a feasible choice to simulate the compound eye system on the curved surface.

To solve the above problems, an array spherical bionic compound eye system is designed in this paper. The relationship between the subsystems on each ring and the field of view angle of the compound eye system is analyzed. The mechanical arrangement among the subsystems is calculated systematically, which makes the system more compact on the mechanical mechanism and ensures that there is no blind area in the detection area. Compared with the traditional large field of view single hole optical system, the system greatly reduces the chromatic aberration and distortion of the system, resolves the contradiction between large field of view and high resolution, and increases the aperture value of the sub-eye. In addition, the detector array with curved surface distribution improves the acquisition ability of target azimuth information.

2. Mathematical model of field of view stitching
According to the design, each sub-eye is considered as an independent optical system. Firstly, the number of loops in the system is determined by the angle of view in the meridian (X) direction, and then the number of subsystem cycles in each ring is determined by the arc-sagittal non-blind area splicing. Secondly, the overall structure of compound eye system is established. Finally, the sub-eye system is designed and optimized.

The relationship of the field of view of the system in the meridional direction is shown in Fig.2. The meridional field of view of the three-ring lens group is taken as an example. Subsystem 1
represents the central optical system, subsystems 2 and 3 represent the primary subsystem and the secondary subsystem. The total field of view of the system is $2\omega$, the angles of view of subsystems 1, 2 and 3 in the meridional direction are $\Phi_1, \Phi_2$ and $\Phi_3, \theta_1$ and $\theta_2$ are the angles of the optical axes of adjacent subsystems. In the target positioning, in order to meet the field of view without blind spots. Considering the mechanical spacing, the above parameters should meet the following conditions [12,13];

$$\begin{align*}
\Phi_1 + \Phi_2 & \geq \theta_1 \\
\Phi_2 + \Phi_3 & \geq \theta_2 \\
\omega & = \theta_1 + \theta_2 + \Phi_3
\end{align*}$$

(1)

According to the determined elements in meridian direction, the arc-sagittal field of view splicing is realized by the circular array of subsystem lenses. The field of view splicing can be guaranteed without blind area under the critical condition. Assuming that the size of the selected detector is $x \times y$, and the space size of the field of view of the image square with the working distance $L$ is $X \times Y$, according to the conjugate relation between the object and the image:

$$\begin{align*}
X &= 2L \tan \Phi_x \\
Y &= 2L \tan \Phi_y
\end{align*}$$

(2)

The $X$-direction edge field of view angle of compound eye $i$-ring array is $\theta_{ix}$, then

$$W\alpha = \Delta \theta_i + \Phi_x$$

(3)

When the distance is $L$, the field of view of the compound eye system is a circular. The spherical radius is $R$. The spherical circumference is $C$.

$$R = L \sin W\alpha$$

$$C = 2\pi R = 2\pi L \sin W\alpha$$

(4)

The edge field of view of the subsystems on each ring is connected to each other, which as a critical splicing condition of the $Y$ field of view;

$$n_i = \frac{2\pi L \sin W\alpha_x}{Y} = \frac{2\pi L \sin W\alpha_y}{2L \tan W\alpha_y}$$

(5)

According to the basic principles of the geometric optics,

$$\begin{align*}
\tan W\alpha_x &= \frac{x_i}{2f} \\
\tan W\alpha_y &= \frac{y_i}{2f}
\end{align*}$$

(6)

According to the $W\alpha_x, W\alpha_y$ given by formula (6), the number of cycles is

$$n_i = \frac{\pi \sin(\Delta \theta_i + \arctan(\frac{x_i}{2f}))}{\frac{y_i}{2f}}$$

(7)

When the actual number of cycles of each ring $N_i \geq n_i$ [12], the entire compound eye system is successively combined in the sagittal direction, and there is no blind zone in the field of view.

3. **System design**

According to the above relationship, the structural design is carried out, and an industrial camera with
a parameter value of 1/2° is selected. The image size of the detector is 6.4 × 4.8 mm, and the size of the selected camera casing is 50 × 50 × 42 mm. The optical system lens has a total length of approximately 54 mm, and the camera projection has a width of 12 mm on the torus of the front view, then the total length is 66 mm. As shown in Fig.3, where B is a side view of the compound eye system, A is a torus front view of the subsystem 2. We treat the lens group as a straight line and the camera as a rectangular. If the lens system does not coincide, the area of the rectangular projected by the camera on the ring, which does not coincide. According to the geometric relationship, the torus radius (the radius of the A circle) on the subsystem 2 is approximately 160 mm. From the radius of the A circle and the angle between adjacent systems, it can be determined that the outer spherical radius is approximately 662 mm and the inner radius is 653 mm. In the actual operation, a structure larger than the above critical parameters can be adopted.

![Fig.3 Side view of the compound eye system and front view of the torus](image)

Based on the above mathematical model and system structure, a set of bionic compound eye optical system for visible target observation is designed. When the actual number of cycles is greater than the theoretically calculated value \( n_1 = 9.8 \), it can be calculated that there is no blind zone in the field of view from the above mathematical model. The accuracy of the mathematical model is proved by geometric methods. We take the total length of the central optical system as the radius, According to the formula (2), \( Y = 12.25 \) can be obtained. Then we take the full length of the edge optical system as the edge object image spacing, \( R = 18.38 \) can be obtained by the formula (4), and the image field space \( X \times Y \) is sequentially connected as the condition of the blind field splicing in the field of view, the rotation half angle is \( t = YR/2 = 18.43° \), the number of cycles is \( n = 2\pi/2t = 9.76 \). Since the number of cycles can only take integers, the results of geometric analysis are consistent with the mathematical model, which proves the accuracy of the mathematical model.

In the design process, we refer to the functional partitioning characteristics of the insect compound eye system, this design reduces the system aberration by improving the traditional single lens compound eye system. The sub-eye of the system is divided into two parts, which include the central sub-eye system and the edge sub-eye system. From the resolution formula \( \tan \Delta \varphi \approx s/f' \) (s is the detector pixel size), it can be seen that the central field of view is small, the resolution is high, and the target is highly accurately recognized, the edge system has a large field of view and low resolution, targets can be searched and captured over a wide range. The parameters of each eye are shown in Table 1.

| Table 1. The main parameters of sub-eye |
|---------------------------------------|
| **Central optical system**             |
| Detector size                         | 6.4 × 4.8 mm |
| Focal length,  f'                      | 36 mm        |
| Field of view                         | 5.08° × 3.81° |
| F number                              | 3            |
| **Edge optical system**               |
| Detector size                         | 6.4 × 4.8 mm |
| Focal length,  f'                      | 20 mm        |
| Field of view                         | 9.09° × 6.84° |
| F number                              | 2.6          |

The pixel size of the detector is 6 \( \mu m \). According to the resolution formula, the limit angle
resolution of the central optical system is $\Delta \varphi_c = 0.00955^\circ$, the edge optical system is $\Delta \varphi_e = 0.017^\circ$.

The structural diagrams of the optical system are shown in Fig.4, Fig.5 and Fig.6. They are used to evaluate the image quality of the central optical system, which include spot diagram, modulation transfer function (MTF). In the spot diagram, the RMS radius of each field of view is less than $0.6 \mu m$ pixel size of detector. The maximum geometric(GEO) radius is less than 3 times than the root mean square(RMS) value. The detector cut-off frequency is $v_d = 1 mm / (2 \times s) = 83 lp / mm$. In the modulation transfer function (MTF), the total sub field MTF of the central sub-eye is greater than 0.5 at 75 lp/mm, the full field of view MTF is greater than 0.3 at 144 lp/mm. The full field of view of the edge sub-eye is greater than 0.5 at 54 lp/mm, the full field of view MTF is greater than 0.3 at 78 lp/mm, so the designed system meets the requirements.

Using the relationship between the system's field of view and the sub-eye system, the structure of the compound eye system is designed which is combined with the formulas (1) to (7). To achieve a field of view of 79.5° for the full field of view, the central field of view is chosen to be $\Phi_1 = 4^\circ$. The edge field of view is $\Phi_2, \Phi_3 = 10^\circ$ for design. The angle of the optical axis in the system is $\theta_1 = 12.9^\circ$ and $\theta_2 = 17.76^\circ$ respectively, and the total angle of view is $2W = 2(\theta_1 + \theta_2 + \Phi_{3.3}) = 79.5^\circ$.

![Fig.4 The structural diagrams. (a represents the center eye, b represents the edge of the eye)](image)

![Fig.5 The spot diagram. (a represents the center eye, b represents the edge of the eye)](image)

![Fig.6 The modulation transfer function (MTF). (a represents the center eye, b represents the edge of the eye; the x axis is Spatial Frequency in cycles per mm, y axis is Modulus of the OTF)](image)
4. Conclusion

According to the mathematical model between the compound eye and the sub-eye system, a set of compound eye system including a 3-ring lens group is designed. The problem that the traditional single aperture lens has a large field of view and high resolution is difficult to achieve at the same time is solved, and the accuracy of the mathematical model is proved by the geometric structure design. The designed compound eye system can achieve a full field of view of 79.5° degrees, we can increase or decrease the number of system lens rings according to different field of view requirements. The simulation results show that there is no blind zone in the field of view within a certain working distance range. Compared with the traditional large field of view lens, the image quality of the edge field of the subsystem is more excellent. The mathematical model and geometric structure proposed in the paper provide a theoretical reference for the design of large aperture bionic compound eye system.

References

[1] Yang J J, Flores A, Wang M R. Achromatic hybrid refractive-diffactive lens with extended depth of focus[J]. Applied Optics, 2004, 43(30):5618.

[2] Tanida J, Kumagai T, Yamada K, et al. Thin Observation Module by Bound Optics (TOMBO): Concept and Experimental Verification[J]. Applied Optics, 2001, 40(11):1806-1813.

[3] Jacques Duparré, Dannberg P, Schreiber P, et al. Artificial apposition compound eye fabricated by micro-optics technology[J]. Applied Optics, 2004, 43(22):4303-10.

[4] Jacques Duparré, Schreiber P, André Matthes, et al. Microoptical telescope compound eye[J]. Optics Express, 2005, 13(3):889-903.

[5] Jeong K H, Kim J, Lee L P. Biologically Inspired Artificial Compound Eyes[J]. Science, 312.

[6] Jacques Duparré, Radtke D, Andreas Tümmermann. Spherical artificial compound eye captures real images[J]. Proceedings of SPIE - The International Society for Optical Engineering, 2007, 6466.

[7] Floreano D, Pericetcamara R, Viollet S, et al. Miniature curved artificial compound eyes.[J]. Proc Natl Acad Sci U S A, 2013, 110(23):9267-9272.

[8] Camara R P, Vila G B, Lecoeur J, et al. Miniature artificial compound eyes for optic-flow-based robotic navigation[C]// Workshop on Information Optics. IEEE, 2014.

[9] Di S, Du R X. Optimal design of single-layer spherical compound eye imaging system[J].Opto-Electronic Engineering, 2010, 37(2):27-31

[10] Li F, Chen S, Luo H, et al. Curved micro lens array for bionic compound eye[J].Optik-International Journal for Light and Electron Optics, 2013, 124(12):1346-1349

[11] Song Y M, Xie Y Z, Viktor.M, Xiao J L, et al. Digital cameras with designs inspired by the arthropod eye.[J]. Nature, 2013, 497(7447).

[12] Fu Y G, Zhao Y, Liu Z Y, et al. Design of the Bionic Compound Eye Optical System Based on Field Splicing Method [J].Chinese Journal of Scientific Instrument, 2015, 36(2):422-429. (in chinese)

[13] Yan F, Guo Y Z, Shi L F, et al. Research of Image Mosaic Algorithm Based on Bionic Compound Eye System [J]. Aero Weaponry, 2017(6):49-53. (in Chinese)