Design and analysis of optical system of semi-active laser seeker

Xiaoqin Pu\textsuperscript{a}, Yawen Du\textsuperscript{b} and Quanlin Dong\textsuperscript{*}

School of Instrumentation Science and Opto-electronics Engineering, Beihang University, Beijing, China

\textsuperscript{*}Corresponding author e-mail: dongquanlin@buaa.edu.cn, \textsuperscript{a}18810951715@163.com, \textsuperscript{b}duyawen@buaa.edu.cn

Abstract. The laser seeker is an important part of navigation guided weapons. The working principle of the laser seeker was expounded, and the optical system of the seeker was designed according to the system index requirements. Its optical system is mainly composed of a receiving optical lens combination and a four-quadrant detector. According to the system performance and technical indicators such as the detection distance of the seeker, the receiving clear aperture, and distortion, the laser imaging spot diameter and the center position range were simulated. The optical system model was established by using CODE-V software. And the spot quality was optimized and evaluated through distortion, trace map, and radial envelope energy curve. Finally, an optical system that satisfies the requirements is designed, and the spot imaging quality is great, and the angular tracking accuracy reaches 0.10\textdegree/\text{s}.

1. Introduction

Laser-guided weapons have achieved good results in recent years, and they have high accuracy, low cost, high power, and easy to use. At present, countries are rushing to develop laser-guided weapons. China has also developed a variety of guided weapons, but it started late, there is a huge gap with other developed countries, and the precision of self-developed laser semi-active guided weapons needs to be improved. Therefore, research, absorption, manufacturing and exploration of guided weapons are still needed [1, 2]. The seeker as the "brain" of the guided weapon controls the entire guided weapon. Based on the existing research, this paper mainly studies the optical system of the semi-active laser seeker, analyzes the working principle of the detector, and According to the requirements of the system, the laser spot diameter and the center position range of the laser spot were calculated and simulated. CODE-V software was used to complete the design, optimization and imaging quality evaluation of the optical system. Finally, the designed and processed optical system was tested, and the system's angular tracking accuracy was higher than 0.10\textdegree/\text{s}, which met the design requirements. The designed optical system can be used as a reference for the design of other optical systems, and it provides credible materials for future research on guided weapons.
2. The optical system design

2.1. The Working principle of laser seeker
The four-quadrant detector is a receiver for target laser signals. In order to obtain the target spot, it is placed at the defocus position of the optical system. The missile control system controls the missile's vertical rudder and horizontal rudder by analyzing and processing the light signals received by the detector to change the missile's flight status, and continuously corrects its flight direction until it accurately targets the attack target [3]. Its working principle is shown in Fig. 1. As shown, when the light spot falls on the detector, four voltages are generated: V1, V2, V3, and V4. The spatial position of the light spot, which is the light spot center (X, Y), is obtained through four-quadrant addition and subtraction.

![Figure 1. Laser facula and four quadrant detector.](image)

By analyzing the internal relationship between the size and central location of the spot and the detector, and considering the linearity of the spot, the following expression is obtained:

\[
V_x = \frac{1}{\pi} \cdot 2K_x \left[ \frac{x}{r} \sqrt{1 - \left( \frac{x}{r} \right)^2} + \arcsin \left( \frac{x}{r} \right) \right] \quad (1)
\]

\[
V_y = \frac{1}{\pi} \cdot 2K_y \left[ \frac{y}{r} \sqrt{1 - \left( \frac{y}{r} \right)^2} + \arcsin \left( \frac{y}{r} \right) \right] \quad (2)
\]

Vx and Vy is the error voltage signal in x and y directions, K is the amplifier gain, x is the horizontal displacement of the spot center, y is the vertical displacement of the spot center, and r is the radius of the receiving spot. It can be seen that the detection of four quadrant signal is related to the spot radius and its center position. Therefore, before designing the optical system of laser seeker, it’s necessary to determine the spot radius and center position range.

According to formula (1), (2) and the diameter of four-quadrant APD, the normalized amplitude of the angular deviation voltage signal at different spot sizes and positions is obtained after normalization using MATLAB, as shown in Fig. 2.
From the simulation analysis, it can be seen that the angle deviation is smaller when the spot radius is $3 / 7 R \sim 4 / 7 R$, and the literature shows that the spot radius is most suitable when the spot radius is half the detector size [4, 5, 7]. According to the technical index requirements that the size of the detector is 10mm, so the spot radius should be between $(4.2856, 5.7142)$ mm, and the center of the spot should be between $[-2.5\text{mm}, 2.5\text{mm}]$.

2.2. Index requirements and analysis of optical system design

The main index requirements of the optical system:

1) Working band: 1064nm ± 2.5nm;
2) Instantaneous field of view angle: ± 15° ± 0.5°, the linear area is not less than ± 5°;
3) Working distance: ≥3.5km;
4) Working method: single quadrant;
5) Photosensitive surface size: Φ10mm;
6) Receiving clear aperture: Φ32mm;
7) System distortion: ≤1%.

The analysis and calculation of the external parameters show that the value range of the spot radius is $[2.1428\text{mm}, 2.8576\text{mm}]$. According to the index requirement of the linear range of the optical system not less than ± 5° and the detector radius $R = 5\text{mm}$, so the maximum spot radius $r$ is 2.8576mm. In order to obtain the complete laser energy, the center position of the imaging spot in the 5° field of view direction must fall within a circular area with a radius of $R_1$ and meet the following condition:

$$R_1 < R - r$$  \hspace{1cm} (3)

That is, the image height $y$ of the main ray with a linear field of view of ± 5° is less than 2.1424 mm, as shown in Fig.3.
Figure 3. Schematic diagram of the main field imaging area of the edge field.

$O_1$ is the center point, the farthest position of the imaging spot center in a $5^\circ$ linear field of view is $O_2$. At this time, the edge of the spot acquired in this field of view is just on the detector. Therefore, the center of the light spot must fall within the circle with $O_1$ as its center and $O_1O_2$ as the radius to meet the requirements.

According to the following relationship between the focal length of optical system and the image height, the system focal length $f \leq 24.4877$ mm is obtained.

$$y = f \times \tan \omega_{\text{linear}}$$

(4)

In addition, the focal length of the optical system and the angle view of the seeker have the following relationship:

$$D = 2f \tan \omega$$

(5)

When the diameter of the detector photosensitive surface is determined as $D = \Phi 10$ mm, according to the maximum field angle $\omega = 15^\circ$, from the calculation of formula (5), the focal length of the optical system is $f \geq 18.66$ mm, that is to say, the focal length of the optical system should be within the range of $[18.66 \text{ mm, } 24.49 \text{ mm}]$.

The formula for relative aperture of the optical system is $D/f$, so the relative aperture can be obtained according to the technical index and the focal length. The index requirements indicate that when the system's field of view is $\pm 15^\circ \pm 0.5^\circ$, the system's entrance pupil is $\Phi 32$ mm, and the critical focal length is 18.66 mm, so the relative aperture is

$$\frac{D_{\text{entrance pupil}}}{f} = \frac{32}{18.66} \geq 1$$

(6)

That is to say, the $F$ number on the image side should be greater than or equal to 0.58. The analysis of the system performance requirements shows that the designed optical system is a near-infrared receiving system with a large field of view, large relative aperture, and short focal length.

3. optical system simulation and analysis

3.1. Determination and simulation of the optical systems

Considering that the system requires a large field of view and high imaging quality, and mainly uses laser light, a refraction optical system is designed. Compared with the reflection, the designed refraction optical system with more adjustable variables can meet the requirements of large field of view and high imaging quality. The optical system model of the seeker is established by the optical design software
CODE-V, and the performance of various indicators of the image plane under the light trajectory is analyzed to optimize and improve the imaging quality. Finally, the optical system that meets the system requirements is obtained after Quick Focus processing as shown in Fig. 4. The specific optical parameters are: entrance pupil diameter $D = 32\text{mm}$, image side $F$ number $= 0.63$, system focal length is $20.27\text{mm}$, spot diameter $\Phi = 5\text{mm}$, and total system length is $31.77\text{mm}$.

![Figure 4. The ray tracing](image-url)

### 3.2. Optical system analysis
The optical system of Laser Guidance Seeker is a non-imaging system. After passing through the system, the light no longer converges at a point in the image space but forms a diffuse spot, and the main concern is the stability of the spot and the uniformity of the energy distribution. Therefore, difference from the evaluation method of the traditional imaging optical system, it generally evaluated by the distortion of the system, the trace of the light spot and the energy distribution diagram of the radial envelope [5, 6].

![Figure 5. The fast field diagram](image-url)
Distortion is a function of the field of view. The actual vertical magnification of different fields of view is different, so the distortion is also different. The larger the field angle, the larger the distortion. Figure 5 shows the distortion map within 5° of the linear field of view, which is the maximum distortion value of the system. As can be seen from the figure, the maximum distortion of the system is 0.48338%, less than 1%, when the linearity is less than or equal to 5°, so the design meets the requirements.

The light footprint diagram shows the position of the imaging spot on the sensitive surface of the detector in the range of 0°, ± 5°, and ± 15°. It can be seen that within a linearity range of 5°, the energy of the light falling on the photosensitive surface is 100% and the light footprint is within the four quadrants of the detector. From the text information corresponding to Fig. 6, the maximum diameter of the light spot can be known. It is 5.05mm, and there is no loss of energy in a quadrant due to the spot size or improper center position, which meets the design requirements.

Figure 6. The light footprint diagram

The enclosing energy distribution curve describes the distribution of the spot energy with diameter in different fields of view. Assuming that the spot energy distribution is uniform, then there is a parabolic relationship between the spot energy and the spot diameter [8]. Fig. 7 shows the concentrated energy distribution in the field of view of 4°, 6°, 8°, and 10°. It can be seen that the spot energy distribution at the spot diameter is approximately a quadratic curve, and the energy distribution is stable and meets the design.
4. Experimental verification
The designed optical system was processed and a two-dimensional precision turntable was used to simulate the rotation of the heading and elevation angles to build a test platform. The test connection is shown in Fig. 8.

Field of view tracking accuracy is an important indicator of the evaluation system. Start the precision turntable along the pitch and yaw directions from ± 15° to ± 0.2° / s, ± 0.5° / s, ± 1° / s, and ± 2° / s, ± 3° / s, ± 4° / s, ± 5° / s speed movement, get the data shown in Table 1, the results show that the angular velocity accuracy is better than 0.10 ° / s, which meets the requirements of the index.
Table 1. Tracking angle accuracy table.

| Angle of turntable(°/s) | Test system angle(°/s) | Absolute mean error |
|-------------------------|------------------------|---------------------|
|                         | Positive               | Negative            |                     |
| Heading angle: ±0.2     | 0.1083                 | -0.3010             | 0.09635             |
| Heading angle: ±0.5     | 0.3969                 | -0.5946             | 0.09885             |
| Heading angle: ±1       | 0.8914                 | -1.0898             | 0.0992              |
| Heading angle: ±2       | 1.8891                 | -2.0914             | 0.0994              |
| Heading angle: ±3       | 2.8860                 | -3.0892             | 0.0997              |
| Heading angle: ±4       | 3.8686                 | -4.0825             | 0.0991              |
| Heading angle: ±5       | 4.8697                 | -5.0665             | 0.0984              |
| Pitch angle: ±0.2       | 0.2677                 | -0.1362             | 0.06575             |
| Pitch angle: ±0.5       | 0.5665                 | -0.4323             | 0.0671              |
| Pitch angle: ±1         | 1.0625                 | -0.9302             | 0.06615             |
| Pitch angle: ±2         | 2.0710                 | -1.9298             | 0.0706              |
| Pitch angle: ±3         | 3.0771                 | -2.9290             | 0.07405             |
| Pitch angle: ±4         | 4.0691                 | -3.9223             | 0.0734              |
| Pitch angle: ±5         | 5.0753                 | -4.9235             | 0.0759              |

5. Conclusion

An optical system for a semi-active laser seeker was designed. Based on the guidance principle of the seeker and based on the system index requirements of a four-quadrant detector, the spot size and the center position of the spot were simulated and analyzed. The optical system was completed using CODE-V. Design and global optimization. Using typical indicators such as distortion, trace map, and radial envelope energy curve for analysis and evaluation, compared with the existing optical systems, there are more adjustable variables to achieve the requirements of large field of view and high imaging quality, and the spot size and center position Reasonable distribution, uniform spot energy distribution, and small system distortion. Finally, according to the design and processing, a miniaturized optical system with a field of view of ± 15° was developed. The angular tracking accuracy was better than 0.10, which verified the correctness of the design and satisfied the system.

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