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# Co-design method for electro-optical imaging systems

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**Abstract**：In the traditional design of electro-optical imaging systems，the optical and electronic subsystems are designed separately. This leads to a reduction in the level of coordination between the parameterization of the both subsystems，resulting in imperfect subsystem compatibility. In order to improve the compatibility between subsystems，shorten a design time and reduce the developments，we propose a co-design method. Based on the end-to-end optoelectronic performance evaluation，the multi-objective and multi-parameter optimization algorithm is used to optimize the configuration parameters of the optoelectronic subsystem. A space infrared imaging system was optimized by this method and imaged good pictures in orbit. The results show that the method has a positive role in optimizing the configuration parameters of the electro-optical imaging system and evaluating the performance of the electro-optical imaging system.

**Key words**：imaging systems，co-design method，end-to-end evaluation，stray light.

**PACS**：07. 57. Kp，07. 07. Df，07. 05. Tp

# 光电成像系统的协同设计方法研究

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**摘要**:在传统的光电成像系统设计中,光学子系统和电子学子系统是分开设计的.这导致两个子系统的参数化之间协调程度降低,导致子系统兼容性不完善.为了提高各子系统之间的兼容性,缩短设计时间,减少开发成本,本文提出了一种协同设计方法.在端到端光电性能评价的基础上,采用多目标多参数优化算法对光电成像系统的配置参数进行优化.利用该方法对空间红外成像系统配置参数进行了优化,且获得良好在轨成像效果.结果表明,该方法对优化光电成像系统的参数配置,评价光电成像系统的性能具有积极的作用.

**关 键 词**:成像系统;协同设计方法;端到端评价,杂散光

**中图分类号**:O435.2　　**文献标识码**:A

## Introduction

In the design of electro-optical imaging systems，the parameters of electronic and optical subsystems are usually obtained in two distinct design steps[1]. The development of both optical and electronic technologies has enabled more flexibility in designing each subsystem；however，this flexibility may also lead to incompatibility between these two subsystems. Although the optical and electronic subsystems can achieve excellent performances，they may be mismatched. After “gluing” the separate subsystems together，the end result of the design may not be optimal in terms of the system performance or cost effectiveness ratio[2-3]. Furthermore，distinct design steps make it difficult for designers to estimate and balance the manufacturing complexity of the overall system. Clearly，designing a system using end-to-end performance evaluation models that involve both optical and electronic subsystems will solve the mismatching problem，ensure compatibility，and improve analysis and de-

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sign efficiencies, which will lead to more effective electro-optical imaging systems. Even though some approaches based on the overall system's modulation transfer function (MTF) have been suggested, [1,4-6] the number of parameters—such as pixel size, fill factor, focal length, and numerical aperture—involved in the MTF function is too small to sufficiently support designers in analyzing and designing the overall electro-optical system. Brief models including MTF, signal-to-noise ratio (SNR) and dynamic range (DR) have been used to evaluate the performance of imaging system; [7-8] however, these models are oversimplified and do not consider noise induced by stray light, which is a very important factor in analyzing the performance of space imaging systems. [9]

In this paper, a co-design method is proposed, which uses multi-objective and multi-parameter optimization algorithm to design electro-optical imaging system efficiently. The principles of the method are introduced in Sect. 1. In the electro-optical imaging system optimization process, the end-to-end performance evaluation SNR, DR and noise-matching factor are used as merit functions, which reflect both electronic and optical parameters, especially considering the influence of stray light. In Sect. 2, an example of a co-designed space infrared imaging system is provided, the simulation demonstrates the feasibility of the co-design method. Finally, brief conclusion is given in Sect. 3.

# 1 Co-design method

## 1.1 End-to-end performance evaluation

A schematic of an electro-optical imaging system is shown in Fig. 1. In a space electro-optical imaging system, both the operating environment and the optical system induce stray light into the system. [8] The target light and stray light are converted to electrical signals by a sensor, and then the readout circuit amplifies and samples the resulting electrical signal. In this process, optical noise is added (shot noise caused by the target and stray lights), and electronic noise is generated during electric signal processing.

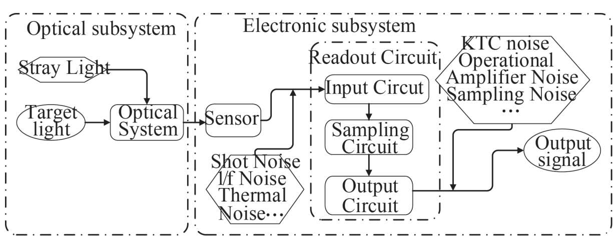


Fig. 1 Schematic of the electro-optical imaging systems
图1 光电成像系统原理简图

The performance of electro-optical imaging systems depends on several aspects, including SNR, DR, MTF, field of view, spatial resolution, and so on. In this paper, SNR and DR are used simultaneously to evaluate the performance of optimized electro-optical imaging systems because to some extent, they reflect both optical and electronic performance.

The SNR is defined as a ratio between signal energy and noise energy, which can be given as

$$\mathrm{SNR} = \frac{I_{\mathrm{sig}}}{\bar{I}_{\mathrm{n}}} \quad , \quad (1)$$

where $\bar{I}_{\mathrm{n}}$ is the noise current and $I_{\mathrm{sig}}$ is the photoelectric current of the target light. When the target light is emitted by the radiation of the target, $I_{\mathrm{sig}}$ can be expressed as

$$I_{\mathrm{sig}} = \mathrm{e}\cdot\frac{\eta_i}{hc}\lambda\cdot A\cdot\tau_a\cdot\tau_0\cdot\varepsilon\cdot\int_{\lambda_1}^{\lambda_2}\frac{2\pi c^2 h}{\lambda^5\left(\mathrm{e}^{\frac{hc}{\lambda k_B T_e}}-1\right)}\mathrm{d}\lambda\cdot\frac{1}{4F^2} \quad . \quad (2)$$

In Eq. 2, $c = 3.0\times10^8$ m/s represents the speed of light, $h = 6.626\times10^{-34}$ J/s is Planck's constant, $k_B = 1.38\times10^{-23}$ *J/K* is the Boltzmann constant, $\lambda_1$ and $\lambda_2$ are the endpoints of the sensor's operating wavelength range, A is the sensor's pixel area, $\eta_i$ is the sensor's quantum efficiency, $T_e$ is the target temperature, $\tau_0$ is the optical efficiency, $\tau_a$ is the atmospheric transmissivity, $\varepsilon$ is the surface emissivity, $e = 1.6\times10^{-19}$C is the basic electric charge, and F is the F-number of the optical subsystem.

Noise current $\bar{I}_n$ can be expressed as the root-mean-square of the sensor noise current and the readout circuit noise current as

$$\bar{I}_{\mathrm{n}} = \sqrt{\bar{I}^2_{\mathrm{n,sensor}} + \bar{I}^2_{\mathrm{n,readout}}} \quad . \quad (3)$$

The sensor noise in electro-optical imaging systems mainly includes thermal noise and shot noise, especially in infrared imaging systems. The shot noise consists of both photoelectric current and dark current shot noises. Photoelectric noise current is the shot noise current caused by the target and stray lights. Considering that the stray light varies according to the operating environment and optical system in space infrared imaging systems, we introduce the signal-to-stray ratio (SSR), which represents the ratio of target light energy to stray light energy, to estimate the power of stray light. Assuming a fundamentally linear relationship between the energy of light and the photoelectric current, the SSR can be expressed as

$$\mathrm{SSR} = \frac{E_{\mathrm{sig}}}{E_{\mathrm{sc}}} = \frac{I_{\mathrm{sig}}}{I_{\mathrm{sc}}} \quad , \quad (4)$$

where $E_{\mathrm{sig}}$ is the energy of target light, $E_{\mathrm{sc}}$ is the energy of stray light, $I_{\mathrm{sig}}$ is the photoelectric current of the target light, and $I_{\mathrm{sc}}$ is the photoelectric current of stray light.

Thus, the sensor noise current can be expressed as

$$\bar{I}^2_{\mathrm{n,sensor}} = \frac{\frac{2k_B T}{R_{\mathrm{sensor}}} + \mathrm{e}\left(\left(1 + \frac{1}{\mathrm{SSR}}\right)I_{\mathrm{sig}} + I_{\mathrm{dc}}\right)}{T_{\mathrm{int}}} \quad , \quad (5)$$

where $R_{\mathrm{sensor}}$ is the sensor resistance, $I_{\mathrm{dc}}$ is the dark current, $T_{\mathrm{int}}$ is the integration time, and $T$ is the sensor operating temperature.

The readout circuit noise includes the operational amplifier circuit noise $\bar{V}^2_{\mathrm{out,op}}$, kTC noise $\bar{V}^2_k$, sampling noise $\bar{V}^2_{\mathrm{sh}}$, output noise $\bar{V}^2_{\mathrm{sf}}$, and power noise $\bar{V}^2_{\mathrm{out,power}}$. Different types of operational amplifier circuits have different electronic noise forms. In this study, we focus on the noise of operational amplifiers of capacitive transimpedance amplifier circuits, which is expressed as

$$\overline{V}_{\mathrm{out,op}}^2=\frac{8\pi k_B T}{3C_c}\left(\frac{C_{\mathrm{sensor}}+C_{\mathrm{int}}}{C_{\mathrm{int}}}\right) \quad . \quad (6)$$

In Eq. 6, $C_{\mathrm{sensor}}$ is the sensor capacitance, $C_{\mathrm{int}}$ is the integration capacitance, and $C_c$ is the Miller capacitance. The kTC noise is that

$$\overline{V}_k^2=\frac{k_B T}{C_{\mathrm{int}}} \quad . \quad (7)$$

In space array charge-coupled-device cameras, the noise of the readout circuit can then be expressed as

$$\overline{I}_{\mathrm{n,readout}}^2=\frac{\left(A_{\mathrm{sf}}^2\left(\overline{V}_{\mathrm{out,op}}^2+\overline{V}_k^2+\overline{V}_{\mathrm{sh}}^2\right)+\overline{V}_{\mathrm{sf}}^2+\overline{V}_{\mathrm{out,power}}^2\right)C_{\mathrm{int}}^2}{A_{\mathrm{sf}}^2 T_{\mathrm{int}}^2}, (8)$$

where $A_{\mathrm{sf}}$ is the circuit gain factor.

DR represents the ratio between the brightest and darkest target lights that an imaging system can detect. Because the photoelectric current of the stray light and the dark current charge the integration capacitance of the sensor, we need to consider their influence on DR, the voltage caused by the stray light and the dark current should be subtracted from the saturation voltage of the integration capacitance.

$$\mathrm{DR}=\frac{V_{\mathrm{sat}}-V_{\mathrm{dc}}-V_s}{\sqrt{\left(\frac{A_{\mathrm{sf}}T_{\mathrm{int}}}{C_{\mathrm{int}}}\right)^2\overline{I}_{\mathrm{n,sensor}}^2+\left(\frac{A_{\mathrm{sf}}T_{\mathrm{int}}}{C_{\mathrm{int}}}\right)^2\overline{I}_{\mathrm{n,readout}}^2}} \quad , \quad (9)$$

where $V_{\mathrm{sat}}$ is the saturation voltage of the integration capacitance, $V_{\mathrm{dc}}$ is the voltage caused by the dark current, and $V_s$ is the voltage caused by the stray light photoelectric current. $V_{\mathrm{dc}}$ and $V_s$ can be expressed as

$$V_{\mathrm{dc}}=A_{\mathrm{sf}}\cdot\frac{T_{\mathrm{int}}}{C_{\mathrm{int}}}\cdot I_{\mathrm{dc}} \quad , \quad (10)$$

$$V_s=A_{\mathrm{sf}}\cdot\frac{T_{\mathrm{int}}}{C_{\mathrm{int}}}\cdot\frac{I_{\mathrm{sig}}}{\mathrm{SSR}} \quad . \quad (11)$$

## 1.2 Noise matching factor

To ensure the compatibility of the optical and electronic subsystems, while optimizing the electro-optical imaging systems, we define the noise-matching factor $\xi$ as

$$\xi=\frac{\overline{I}_{\mathrm{ON}}}{\overline{I}_{\mathrm{EN}}} \quad , \quad (12)$$

where $\overline{I}_{\mathrm{ON}}$ is the current of optical noise (shot noise caused by the target and stray lights), $\overline{I}_{\mathrm{EN}}$ is the current of electronic noise that includes thermal noise, shot noise (caused by dark current), and readout circuit noise. They can be calculated by

$$\overline{I}_{\mathrm{ON}}=\sqrt{\frac{e\left(1+\frac{1}{SSR}\right)I_{\mathrm{sig}}}{T_{\mathrm{int}}}} \quad , \quad (13)$$

$$\overline{I}_{\mathrm{EN}}=\sqrt{\frac{2k_B T}{R_{\mathrm{sensor}}T_{\mathrm{int}}}+\frac{eI_{\mathrm{dc}}}{T_{\mathrm{int}}}+\overline{I}_{\mathrm{n,readout}}^2} \quad . \quad (14)$$

The value of $\xi$ should be selected based on the different operating requirements. Usually, $\overline{I}_{\mathrm{ON}}$ is expected to be smaller than $\overline{I}_{\mathrm{EN}}$ in a space electronic-optical imaging system. In order to avoid any "waste," we recommend assigning values to $\xi$ in the range 0.7~1 in the optimization process.

## 1.3 Optimization of the electro-optical system

We presented a multi-objective and multi-parameter optimization algorithm to design electro-optical imaging system. In this optimization process, the end-to-end performance evaluation SNR, DR and noise-matching factor $\xi$ are used as merit functions, the electronic and optical parameters involved in Eqs. 1-14 including SSR, which express the influence of stray light are the optimized electro-optical imaging system parameters. However, the optimization does not need to be performed on all parameters, because some of these parameters have the same monotonic behavior in merit functions. Table 1 lists the monotonic behavior of parameters for the merit functions SNR, DR and noise-matching factor $\xi$. "↑" means the performance is positive about the parameter, "↓" means the performance is negatively related to the parameter.

**Table 1 Monotonic behavior of parameters for the performance valuations**
**表1 性能评价参数的单调性情况**

| Parameters | Designation | SNR | DR |
|---|---|---|---|
| $A/\mu m^2$ | Pixel area | ↑ | ↓ |
| $\eta_i$ | Quantum efficiency | ↑ | ↓ |
| $T_{\mathrm{int}}/\mu s$ | Integration time | ↑ | ↓ |
| $\tau_0$ | Optical efficiency | ↑ | ↓ |
| $C_{\mathrm{int}}/pF$ | Integration capacitance | ↓ | ↑ |
| $R_{\mathrm{sensor}}/G\Omega$ | Sensor resistance | ↑ | ↑ |
| F | F number | ↓ | ↑ |
| $\overline{\lambda}$ | Average operating wavelength | — | — |
| $A_{\mathrm{sf}}$ | Readout circuit gain | — | — |
| $C_{\mathrm{sensor}}/pF$ | Sensor capacitance | ↓ | ↓ |
| $I_{\mathrm{dc}}/A$ | Dark current | ↓ | ↓ |
| SSR | Signal-to-stray ratio | ↑ | ↑ |
| $T$ | Operating temperature | ↓ | ↓ |

As shown in Table 1, $\overline{\lambda}$ and $A_{\mathrm{sf}}$ are working parameters of electro-optical imaging system, given by the designer according to application and cannot be optimized. $C_{\mathrm{sensor}}$, $I_{\mathrm{dc}}$, $R_{\mathrm{sensor}}$, SSR, and $T$ have the same monotonicity for both SNR and DR; therefore, we only need to assign appropriate values or regions to them in order to meet the design requirements and minimize the complexity of the optimizing process. For the parameters A, $\eta_i$, $T_{\mathrm{int}}$, $\tau_0$, $C_{\mathrm{int}}$, and $F$, we use a genetic algorithm to jointly optimize them, so as to fit the design requirements while forcing the subsystems to meet noise-matching factor $\xi$. Besides, additional parameters and algorithm should be added to the optimization process to complete electro-optical imaging system design and meet further operating requirements. For example, the focal length $f$ and optical aperture D of the optical subsystem can be calculated by the $F$ number and the spatial resolution requirement.

The optimization process of applying the co-design method to a space electro-optical imaging system is shown in Fig. 2.

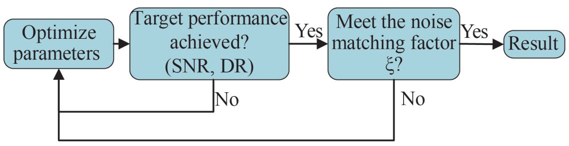


Fig. 2　Co-design method process
图2　协同优化流程

## 2　Application and analysis

Using the co-design method, we optimized a space-based infrared imaging system. The operating requirements are given as Table 2.

**Table 2　Operating requirements**
**表2　设计需求**

| Parameters | Requirements |
|---|---|
| Orbital altitude *R* | 36 000 km |
| Spatial resolution *r* | 1 km |
| Operating wavelength | 3. 5 to 4. 5 μm |
| SNR | > 100 |
| DR | > 1000 |

As mentioned above, we usually expect the infrared optical subsystem to perform a little better than the electronic subsystem; therefore, in this case, we assign $\xi$'s value in the range 0. 7~1. Before optimization, we assign proper constant values to parameters that need not to be optimized, and the range of the variable values to other parameters based on the operating requirement of this case. Table 3 shows the range and proper constant value.

Notice that two specific values for SSR are indicated in this table. In the conventional design method, optical designers attempt to raise the value of SSR as much as possible. However, in space-based infrared imaging systems, the difficulty in manufacturing the optical subsystem increases when the value of SSR increases because the stray light is difficult to control. Therefore, to analyze the imaging effect of using a smaller SSR value, it will be useful to compare the optimized results obtained with two different SSR values.

According to the operating requirements and noise-matching factor, we optimize the system parameters and obtain the co-design results listed in Table 4. As shown in this table, the obtained design results comply with all operational requirements for both values of SSR, and the subsystems are compatible with the selected noise allocation. Most optimized values are similar in the two systems, except $C_{int}$. The value of $C_{int}$ is smaller while meeting the higher SSR. The system with the higher SSR (SSR = 0. 5) can easily attain higher values of SNR; however, it will require cold optics technology, which is considerably costly to implement. The system with lower SSR (SSR = 0. 1) also meets the operational requirements. Considering manufacturing complexity and cost, designers will prefer the optimized system with a smaller SSR, as system 1 shown in Table 4.

According to the optimized design parameters of system 1, the developed camera can operate in orbit and obtain clear and texture-rich images, as shown in Fig. 3.

As demonstrated by this example, the proposed method can help designers quickly analyze all possible designing alternatives in the early design steps of the overall imaging system.

**Table 3　Relevant parameter ranges**
**表3　相关参数取值范围**

| Parameters | | Designation | Type | Range |
|---|---|---|---|---|
| Imaging system | $A$ | Pixel area | Variable | 600 ~1 300 μm$^2$ |
| | $\eta_i$ | Quantum efficiency | Variable | 0. 5~0. 8 |
| | $T_{int}$ | Integration time | Variable | 500 ~1 500 μs |
| | $\tau_0$ | Optical efficiency | Variable | 0. 3~0. 7 |
| | $C_{int}$ | Integration capacitance | Variable | 0. 1~1 pF |
| | $F$ | F-number | Variable | 2~4 |
| | $R_{sensor}$ | Sensor resistance | Constant | 100GΩ |
| | $\overline{\lambda}$ | Average operating wavelength | Constant | 3. 825 μm |
| | $A_{sf}$ | Readout circuit gain | Constant | 1 |
| | $I_{dc}$ | Dark current | Constant | 1E-12 A |
| | $C_{sensor}$ | Sensor capacitance | Constant | 10 pf |
| | SSR | Signal-to-Stray Ratio | Constant | 0. 1/0. 5 |
| | $V_{sat}$ | Saturation voltage | Constant | 2. 5 V |
| | $T$ | Operating temperature | Constant | 100 K |
| Target | $\tau_a$ | Atmospheric transmissivity | Constant | 0. 8 |
| | $T_e$ | Target temperature | Constant | 300 K |
| | $\varepsilon$ | Target emissivity | Constant | 0. 3 |

**Table 4 Optimized parameters**
**表4 优化后的配置参数**

| Category | Parameters | System 1 | System 2 |
|---|---|---|---|
| Imaging system parameters | $A$ | 1 155 $\mu m^2$ | 1 154 $\mu m^2$ |
| | $\eta_i$ | 0. 69 | 0. 67 |
| | $T_{int}$ | 988. 1 $\mu s$ | 994. 5 $\mu s$ |
| | $\tau_0$ | 0. 668 | 0. 683 |
| | $C_{int}$ | 0. 442 pF | 0. 15 pF |
| | $F$ | 2. 523 | 2. 503 |
| | $f$ | 1. 22 m | 1. 22 m |
| | $D$ | 0. 484 m | 0. 487 m |
| | $R_{sensor}$ | 100$G\Omega$ | 100$G\Omega$ |
| | $A_{sf}$ | 1 | 1 |
| | $I_{dc}$ | 2E-12 A | 2E-12 A |
| | SSR | 0. 1 | 0. 5 |
| | $V_{sat}$ | 2. 5 V | 2. 5 V |
| | $T$ | 100 K | 100 K |
| Imaging system performance | $\xi$ | 0. 9 | 0. 86 |
| | SNR | 117. 88 | 223. 8 |
| | DR | 1119. 5 | 1070 |

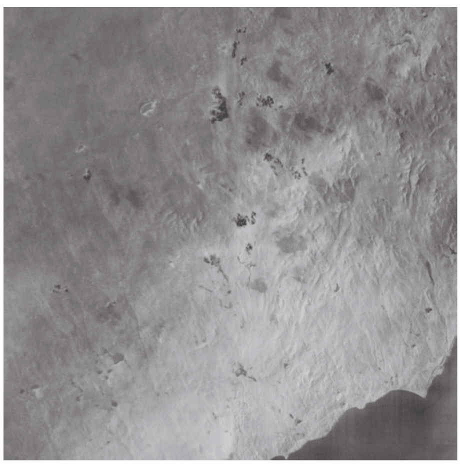

Fig. 3 On-orbit image
图3 在轨图像

## 3 Conclusion

In this paper, we proposed a co-design method for optimizing parameters of space electro-optical imaging systems, which eliminates the traditional separation barrier between the design of the optical and electronic subsystems. To jointly optimize the electro-optical imaging system, end-to-end performance SNR, DR and noise-matching factor were used as merit functions. We proved the efficiency of this method through a design case, which also shows that the proposed co-design method will certainly help and support the designers of electro-optical imaging systems in quickly analyzing and designing a better system.

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