Optical Design of a Shortwave Infrared Dual Camera CASSI Based on Improved Offner-Wynne Imaging Spectrometer

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Abstract. Based on the optical system characteristics of coded aperture snapshot spectral imager (CASSI), an optimized optical system of shortwave infrared dual camera CASSI was designed based on improved Offner-Wynne imaging spectrometer. The operating wavelength of the optical system ranges from 900nm to 1700nm, and the focal length is 1200mm. It consists of two parts: the two dimensional imaging system and the multispectral CASSI imaging system. The key technical parameters of the two parts are the same and there is no visual axis difference. Therefore, the optimized optical system can effectively improve real-time performance, optical transmittance and compactness of the dual camera shortwave infrared CASSI, which is conducive to the application in optical measurement scenes in the shooting range.

Keywords. Dual camera CASSI; Improved Offner-Wynne; Shortwave infrared; Optical design;

1. Introduction
Traditional spectral imaging is often time-consuming and not suitable for measuring dynamic scenes because of the data scanning module [1, 2]. The CASSI can capture spectral imaging of dynamic scenes by a single-frame exposure, and the reason is that the scene is modulated by code aperture and dispersive element which is spatially and spectrally sparse and can be reconstructed by the CS theory [3, 4]. But one coding image is often lack of information, and eventually the peak signal to noise ratio (PSNR) of reconstruct image is too low. Therefore, multiple coding images method and dual camera method are proposed to improve the image PSNR. Multi-frame coding images method loses the most important real-time advantage, but the dual camera method can preserve the real-time advantage of the CASSI [5]. Dual camera method needs to add a two dimensional imaging system, is used to obtain additional two dimensional image to provide more edge and other auxiliary information to improve the quality of multispectral image and reduce the risk of reconstruction[6]. Dual camera CASSI can complete sampling of scene information within one coding and one exposure time. Since only one coding image is performed, there is no need to use complex dynamic coding device inside the dual camera CASSI, which further improves the stability and reliability of the system.

In 2014, Yuri Murakami et al. conducted data acquisition experiments using dual camera CASSI, and the results showed that dual camera CASSI could generate high-resolution multispectral videos at 3 frames per second [7]. In 2015, Masahiro Yamaguchi et al. proved the feasibility of dual camera CASSI, pointing out that this method can effectively solve the problem of low light energy utilization in hyperspectral imaging [8]. In 2017, Laura Galvis et al. came up with a method to maximize the edge information of panchromatic images to enhance the spatial resolution of multispectral images by
taking advantage of the complementary characteristics based on dual camera CASSI [9]. In 2019, Kareth Leen Lopez et al. proposed a spectral video reconstruction method based on dual camera CASSI, which improved the PSNR by 5dB compared with the traditional method [10].

In this paper, we mainly engage in the optical design of a shortwave infrared dual camera CASSI operating in 900-1700nm band, and the optical system is used for long-distance detection. Compared to visible spectrum, the shortwave infrared spectrum has the advantage of better resistance to smoke and fog interference [11]. It should be pointed out that improved Offner-Wynne imaging spectrometer is proposed to improve system compactness and ensure perfect imaging quality in a wider annular region where the code aperture of the shortwave infrared dual camera CASSI can be placed perfectly.

2. Theory

The principle layout of dual camera CASSI is shown in figure 1. The optical system of the shortwave infrared CASSI consists of two parts: the two dimensional imaging system (red dotted rectangle in figure 1) and the multispectral CASSI imaging system (blue solid rectangle in figure 1). The two dimensional imaging system can obtain shortwave infrared image, and the multispectral CASSI imaging system can obtain shortwave infrared multispectral coding image. Since the design method of common aperture is adopted, the two parts have no axial difference of view and the two parts have the same technical parameters, which provides great convenience for the fusion of shortwave infrared image and shortwave infrared multispectral coding image.

![Figure 1. Schematic of dual camera CASSI.](image)

The 3D source information is divided into two parts by a splitting prism. The horizontally rightward beam is concentrated at the detector b through objective lens b, code aperture, collimating lens, dispersive element, imaging lens, and the shortwave infrared multispectral coding image is integrated. The vertically downward beam converging at detector a through objective lens a, forming shortwave infrared image. Ultimately, high PSNR shortwave infrared multispectral image can be obtained by fusing the shortwave infrared image and shortwave infrared multispectral coding image, as shown in figure 2.
In order to improve the transmittance, the compactness, and image quality of the optical system, we designed the improved Offner-Wynne imaging spectrometer to the dual camera CASSI instead of the collimating lens, the dispersive element and the imaging lens. The improved Offner-Wynne imaging spectrometer can be achieved by adding a concentric meniscus lens in the basic Offner imaging spectrometer. Due to the addition of a meniscus lens, the spherical aberration and overall Petzval sum can be greatly decreased [12]. Therefore, in this paper, we propose improved Offner-Wynne imaging spectrometer, which can apply in dual camera CASSI. The dual camera CASSI is designed to detect and analyze the spectral information of the plume from a distant target. Therefore, the working state of the engine can be obtained by analyzing the spectral radiation characteristics of the plume. Based on the application background analysis, the specific design parameters are shown in table 1.

Table 1. Specific design parameters of the shortwave infrared CASSI.

| Parameters          | Value                  |
|---------------------|------------------------|
| Wavelength range    | 900nm–1700 nm          |
| Focal length        | 1200 mm                |
| F-number            | 5                      |
| Spectral resolution | 20nm                   |
| Field angle         | 0.7°                   |
| Spectral smile      | <half a pixel           |
| Keystone            | <half a pixel           |

3. Optical Design
Firstly, we designed the two dimensional imaging system, and then we designed the multispectral CASSI imaging system based on the improved Offner-Wynne imaging spectrometer. Finally, optical system of the shortwave infrared dual camera CASSI was designed on the premise of parameter matching. The two dimensional imaging system is designed in the form of image space telecentricity. Taking into account the field angle and focal length, we used code aperture of 20μm microcomponent size with 512×512 microcomponents, and used shortwave infrared focal plane detector of 20μm pixel size with 640×512 pixels considering the number of spectral bands.

3.1. Optical Design of the Two Dimensional Imaging System
During the optimization of the two dimensional imaging system, the image space telecentricity and the
focal length are used as constraint conditions. The design result shown in figure 3.

![Figure 3. The two dimensional imaging system.](image)

The two dimensional imaging system is evaluated by spot diagrams and the modulation transfer function (MTF). The spot diagram of the two dimensional imaging system presents that the spots are well focused within a 20μm pixel in each field in figure 4. The MTF of the two dimensional imaging system is shown in figure 5, and indicates that the MTF is higher than 0.75 in each field. Therefore, the two dimensional imaging system we designed has excellent performance.

![Figure 4. Spot diagram of the two dimensional imaging system.](image)
3.2. Optical Design of the Multispectral Cassi Imaging System

The multispectral CASSI imaging system was designed based on the improved Offner-Wynne imaging spectrometer. Improved Offner-Wynne imaging spectrometer can effectively reduce the aperture of meniscus lens. Then, we used the constraint conditions: the reduction ratio and the object size, to take further optimization. The two dimensional imaging system and improved Offner-Wynne imaging spectrometer have the same F-number, and their pupil matches well owing to the design of telecentricity, so the two parts can be combined perfectly. The final design result shown in figure 6.

Figure 5. MTF of the two dimensional imaging system.

Figure 6. The multispectral CASSI imaging system.

Figure 7 shows the spot diagram, which indicates that the spots are within a single pixel in each field. Figure 8 shows the MTF curves in 1300nm, 1700nm and 900nm, which indicate the MTFs are all better than 0.65.
In addition, the spectral keystone and spectral smile are also an essential measurement index for spectral imaging systems. This paper acquires these values of the optical system based on real ray tracing. Simulation results indicate that the spectral smile is less than 7.8μm and the spectral keystone is less than 9μm throughout the entire wavelength band. Hence, the spectral smile is less than half a pixel, and so is spectral keystone. In other words, the optical system meets the specific design parameters based on the above analysis.

3.3. Optical Design of the Shortwave Infrared Dual Camera CASSI
The two-dimensional imaging system and the multispectral CASSI imaging system have the same F-number and shortwave detector. The two-dimensional imaging system is imaging on a shortwave detector a, the multispectral CASSI imaging system is imaging on shortwave detector b, and the designed result of shortwave infrared dual camera CASSI is shown in the following figure 9.
Figure 9. Shortwave infrared dual camera CASSI.

4. Conclusion
In this paper, the optical system of shortwave infrared dual camera CASSI is designed which includes two dimensional imaging system and multispectral CASSI imaging system. In addition, we designed an improved Offner-Wynne imaging spectrometer and apply it to the multispectral CASSI imaging system. Simulation results indicate that the spot sizes at each field are far less than 20μm, the MTFs at each wavelength are all better than 0.65, and the spectral smile of the system is less than 9μm. In short, the presented design results illustrate that the performance of the shortwave infrared dual camera CASSI is excellent and meets the practical application requirements.

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