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High-accuracy infrared simulation model based on establishing the linear relationship between the outputs of different infrared imaging systems

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ABSTRACT

Accurately simulating the output of an infrared imaging system is increasingly important for predicting the operational performance of the system under different conditions. Traditional infrared simulation models need to obtain the actual temperature of the simulated scene, which is quite complex and will introduce various error sources. To solve this problem and improve the accuracy of the simulation results, a novel infrared simulation model is proposed by studying the linear relationship between the outputs of different infrared imaging systems in this paper. This work is accomplished mainly by conducting variables separation and linear approximation on the signal transfer function of infrared imaging system and converting geometric resolution between the outputs of different infrared imaging systems. To verify the simulation model, the output of the mid-wave/long-wave thermal imager is simulated by the proposed model based on the measured output of the long-wave/mid-wave thermal imager, and the simulated results are compared with the measured results. Experimental results show that the simulated results have high accuracy.

1. Introduction

Infrared image, which is obtained by infrared imaging system for specific geographical background in certain environment, have been researched extensively for different applications [1–4]. However, it is difficult to obtain the output of an unavailable infrared imaging system (UIIS). Furthermore, the restriction of many circumstances, such as geography and weather, makes it difficult to obtain infrared image under complex environment [5]. To objectively evaluate the operational performance of the UIIS for different conditions, it is necessary to generate the output of the UIIS via infrared scene simulation methods.

Currently there are mainly two ways to simulate the output of an UIIS. The most widely used way is based on the temperature prediction technique, which is often adopted in the commonly used infrared scene simulation software. For example, SE-WORKBENCH-IR [6,7], DIRSIG [8,9], OSSIM [10,11] and CAMEO-SIM [12,13] predict the temperature of the scene according to heat transfer theory, which considers the complex interaction of atmospheric effects, local meteorological conditions, solar load, temperature of the scene, emissivity of the scene, look angle, sensor location, and sensor spectral characteristics [14,15]. Another way is based on temperature inversion technique, which inverses the temperature of the scene based on the output of existing infrared imaging system (EIIS) according to the radiation transfer theory [16]. Then the output of UIIS can be simulated on the basis of the predicted/inversion results according to radiation transfer theory, as shown in Fig. 1.

Since the temperature of the scene is related to a variety of factors, such as material, structure and thermal properties of the scene, atmosphere, surrounding environment, the temperature prediction or inversion process is quite complex and it is difficult to predict or inverse the actual temperature of the scene accurately. Furthermore, a small error in the temperature prediction or inversion results may lead to a wrong infrared simulation results for traditional models, which will mislead us to evaluate the operational performance of the UIIS.

However, if we can establish a linear relationship between the outputs of different infrared imaging systems and cancel out the temperature factor, the output of the UIIS can be simulated simply based on the output of EIIS without predicting or inversing the actual temperature of the scene. Then, the computational complexity will be reduced greatly and the accuracy of the simulated results will be improved remarkably.

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To achieve this, this paper presents a novel infrared simulation model by studying the linear relationship between the outputs of different infrared imaging systems. The main principle of the proposed simulation model is shown in Fig. 2. First, the signal transfer function (SiTF) is introduced to quantify the relationship between the output and the incident irradiance of infrared imaging system. Since the SiTF is a complex function of several variables (such as temperature and wavelength), which makes it difficult to establish the linear relationship between the outputs of different infrared imaging systems, we conduct variables separation on SiTF. Besides, the relationship between the output of infrared imaging system and the temperature of the simulated scene is nonlinear, it is difficult to cancel out the temperature factor during establishing the linear relationship mentioned-above, we conduct linear approximation on the SiTF in small temperature ranges, on the basis of which the SiTF will be a linear function of the temperature factor. Then, we can establish the linear relationship between the outputs of different infrared imaging systems and cancel out the temperature factor during establishing the linear relationship in small temperature ranges. Thus, the output of the UIIS can be simulated by determining the temperature range of the simulated scene instead of predicting or inversing the actual temperature of the scene. However, since the geometric resolution of the output of UIIS and EIIS are different in general, we also study the conversion of geometric resolution between the outputs of different infrared imaging systems. Finally, the simulation model is established by combining the linear relationship and the conversion of geometric resolution between the outputs of different infrared imaging systems.

This paper is organized as follows: In Section 2, the linear relationship between the outputs of different infrared imaging systems is established. In Section 3, we study the conversion of geometric resolution between the outputs of different infrared imaging systems. In Section 4, the infrared simulation model is established. The feasibility of the proposed model is verified in Section 5 and the main achievements are concluded in Section 6.

2. Establishment of the linear relationship between the outputs of different systems

2.1. SiTF model

In order to establish the linear relationship between the outputs of different infrared imaging systems, it is necessary to understand the process of radiation energy transformation in infrared imaging system. Hence, we introduce SiTF, which describes the process mentioned-above and quantifies the relationship between the output and the incident irradiance of an infrared imaging system [17], as given in the following equation [18]:

$$V = \frac{D^2AG}{4f^2}\int_{\lambda_1}^{\lambda_2} R(\lambda)\tau_o(\lambda)E(\lambda,T)d\lambda \quad (1)$$

where D is the diameter of the optical pupil of the system (m), A is the area of the detector photosensitive unit (m^2), G is the gain of the system, f is the focal length of the system (m), $R(\lambda)$ is the spectral responsivity of the system (V/W), $\tau_o(\lambda)$ is the spectral transmittance of the optical components, T is the temperature of the scene (K), $E(\lambda, T)$ is the total incident irradiance (W/(m^2 μm)), including both reflected and thermally emitted radiation, on the entrance pupil. A simplified model describing the $E(\lambda, T)$ is given by [19]

$$E(\lambda,T) = \left[\varepsilon(\lambda)M_b(\lambda,T) + (1-\varepsilon(\lambda))\left(E_{sun}(\lambda) + E_{atm,d}(\lambda) + E_{sun,d}(\lambda)\right)\right]\tau_a(\lambda) + E_{atm,u}(\lambda) + E_{sun,p}(\lambda) \quad (2)$$

where $\varepsilon(\lambda)$ is the spectral emissivity of the target surface, $T_a(\lambda)$ is the atmospheric transmittance along the system-to-target path, $E_{sun}(\lambda)$ is the solar spectral irradiance on the target surface (W/(m^2 μm)), $E_{atm,d}(\lambda)$ is the thermal downwelling irradiance produced by the atmosphere (W/(m^2 μm)), $E_{atm,u}(\lambda)$ is the thermal path irradiance (W/(m^2 μm)), $E_{sun,d}(\lambda)$ is the diffuse solar downwelling irradiance (W/(m^2 μm)), $E_{sun,p}(\lambda)$ is the solar path irradiance (W/(m^2 μm)). $M_b(\lambda, T)$ is the radiant exitance of blackbody (W/(m^2 μm)), which is the integral of the radiance of blackbody over π solid angle. $M_b(\lambda, T)$ can be expressed by blackbody radiation function

$$M_b(\lambda,T) = \int_0^{\pi} L_b(\lambda,T)d\Omega = \frac{C_1}{\lambda^5(e^{C_2/(\lambda T)}-1)} \quad (3)$$

where $L_b(\lambda, T)$ is the radiance of blackbody(W/(sr m^2 μm)), Ω is the solid angle(sr), C_1 and C_2 are constants, $C_1 = 3.74 \times 10^8$ (W μm^4/m^2), $C_2 = 1.44 \times 10^4$ (μm K).

According to SiTF, the relationship between the output of infrared imaging system and the radiation energy of simulated scene is determined, which provides theoretical foundation for us to establish the linear relationship between the outputs of different infrared systems.

2.2. SiTF decomposition

Since the SiTF is a complex function of several variables, which makes it difficult to establish the linear relationship between the outputs of different infrared imaging systems, we decompose the SiTF into two parts, the temperature-related part V_1 and the temperature-independent part V_2, and carry out the separation of variables on V_1.

Decomposing into two parts, the SiTF can be expressed as

$$V = V_1 + V_2 \quad (4)$$

where V_1 and V_2 are given by

$$V_1 = \frac{D^2AG}{4f^2}\int_{\lambda_1}^{\lambda_2} R(\lambda)\tau_o(\lambda)\varepsilon(\lambda)\tau_a(\lambda)M_b(\lambda,T)d\lambda \quad (5)$$

$$V_2 = \frac{D^2AG}{4f^2}\int_{\lambda_1}^{\lambda_2} R(\lambda)\tau_o(\lambda)\left((1-\varepsilon(\lambda))\left(E_{sun}(\lambda)+E_{atm,d}(\lambda) + E_{sun,d}(\lambda)\right)\tau_a(\lambda) + E_{sun,p}(\lambda) + E_{atm,u}(\lambda)\right)d\lambda \quad (6)$$

Then V_1 is related to λ and T, while V_2 is only related to λ. To further separate these variables in V_1, Eq. (5) is deformed into the summation form, which can be expressed as

$$\begin{aligned}
V_1 &= \tfrac{D^2AG}{4f^2}\textstyle\int_{\lambda_1}^{\lambda_2} R(\lambda)\tau_o(\lambda)\varepsilon(\lambda)\tau_a(\lambda)M_b(\lambda,T)d\lambda \\
&= \tfrac{D^2AG}{4f^2}\Big\{\textstyle\int_{\lambda_1}^{\lambda_1+\Delta\lambda} R(\lambda)\tau_o(\lambda)\varepsilon(\lambda)\tau_a(\lambda)M_b(\lambda,T)d\lambda \\
&\quad + \textstyle\int_{\lambda_1+\Delta\lambda}^{\lambda_1+2\Delta\lambda} R(\lambda)\tau_o(\lambda)\varepsilon(\lambda)\tau_a(\lambda)M_b(\lambda,T)d\lambda \\
&\quad + \cdots + \textstyle\int_{\lambda_1+n\Delta\lambda}^{\lambda_2} R(\lambda)\tau_o(\lambda)\varepsilon(\lambda)\tau_a(\lambda)M_b(\lambda,T)d\lambda\Big\} \\
&= \tfrac{D^2AG}{4f^2}\{R(\lambda_{10})\tau_o(\lambda_{10})\varepsilon(\lambda_{10})\tau_a(\lambda_{10})M_b(\lambda_{10},T)\Delta\lambda \\
&\quad + R(\lambda_{11})\tau_o(\lambda_{11})\varepsilon(\lambda_{11})\tau_a(\lambda_{11})M_b(\lambda_{11},T)\Delta\lambda \\
&\quad + \cdots + R(\lambda_{1n})\tau_o(\lambda_{1n})\varepsilon(\lambda_{1n})\tau_a(\lambda_{1n})M_b(\lambda_{1n},T)\Delta\lambda\} \\
&= \tfrac{D^2AG}{4f^2}\sum_{i=0}^{n} R(\lambda_{1i})\tau_o(\lambda_{1i})\varepsilon(\lambda_{1i})\tau_a(\lambda_{1i})M_b(\lambda_{1i},T)\Delta\lambda
\end{aligned} \quad (7)$$

where, $\lambda_{1i} = [(\lambda_1 + i\Delta\lambda) + (\lambda_1 + ((i+1)\Delta\lambda)]/2 = \lambda_1 + (i+1/2)\Delta\lambda$, $\Delta\lambda = (\lambda_2 - \lambda_1)/(n+1)$, n is the number of divided intervals. $R(\lambda_{1i})$ is the responsivity of the system at $\lambda = \lambda_{1i}$. $\tau_o(\lambda_{1i})$ is the transmittance of the optical components at $\lambda = \lambda_{1i}$. $\varepsilon(\lambda_{1i})$ is the emissivity of the scene at $\lambda = \lambda_{1i}$. $\tau_a(\lambda_{1i})$ is the atmospheric transmittance along the system-to-target path at $\lambda = \lambda_{1i}$. $M_b(\lambda_{1i}, T)$ is the radiant exitance of blackbody at $\lambda = \lambda_{1i}$.

With the decomposition and the separation of variables for SiTF, the variables in SiTF are separated, which facilitates us to establish