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Correction of aeroheating-induced intensity nonuniformity in infrared images

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HIGHLIGHTS

- An isotropic total variation correction method is proposed to estimate the additive intensity bias in IR images.
- A half quadratic penalty method is applied to the isotropic form of TV discretization.
- An alternating minimization algorithm is adopted for solving the optimization model.
- The proposed correction method can effectively improve IR image quality.

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ABSTRACT

Aeroheating-induced intensity nonuniformity effects severely influence the effective performance of an infrared (IR) imaging system in high-speed flight. In this paper, we propose a new approach to the correction of intensity nonuniformity in IR images. The basic assumption is that the low-frequency intensity bias is additive and smoothly varying so that it can be modeled as a bivariate polynomial and estimated by using an isotropic total variation (TV) model. A half quadratic penalty method is applied to the isotropic form of TV discretization. And an alternating minimization algorithm is adopted for solving the optimization model. The experimental results of simulated and real aerothermal images show that the proposed correction method can effectively improve IR image quality.

1. Introduction

As an aircraft with an optical seeker flies at high speed, the infrared imaging system is subject to the so-called aero-heating effect. This effect causes the temperatures of aerodynamic flow and optical window to rise rapidly. Thus, aerothermal radiation from both high-temperature flow and optical window is a major threat to the imaging system. The added background-induced noise quickly increases with flight time, which can significantly degrade the signal-to-noise ratio and even drive the detector into saturation [1].

Many successful techniques have been proposed to weaken aerothermal radiation noise. Firstly, the variable-integration-time IR imaging technology has been widely applied to prevent the detector from saturating. IR image sharpness is considerably improved due to lowering the detector's integration time [2]. Secondly, a development effort is underway by the window cooling technology program to design an actively cooled window system for use on hypersonic interceptor forebodies [3,4]. The cooling system provides window temperature control through film cooling using supersonic gas or liquid droplet coolants ejected over the surface of each window. Finally, optical filtering and optimization design of an optical system are means of improving the IR system performance in aerothermal environment. Although those techniques can effectively prevent the IR detector from saturating, the by-products, such as the overall performance degradation and the system design complexity, are significant. To date, few automatic correction methods based on image restoration have been proposed to remove the detrimental intensity nonuniformity in aerothermal images.

In this paper, we propose an efficient solution to remove intensity nonuniformity effect in IR images. The intensity bias field can be computed by using an isotropic TV correction model. A smoothing operator based on weighted least squares (WLS) optimization framework [5] is used to eliminate the influence of image details and noise on the correction model. The workflow of the proposed method is shown in Fig. 1. If the standard deviation of the degraded

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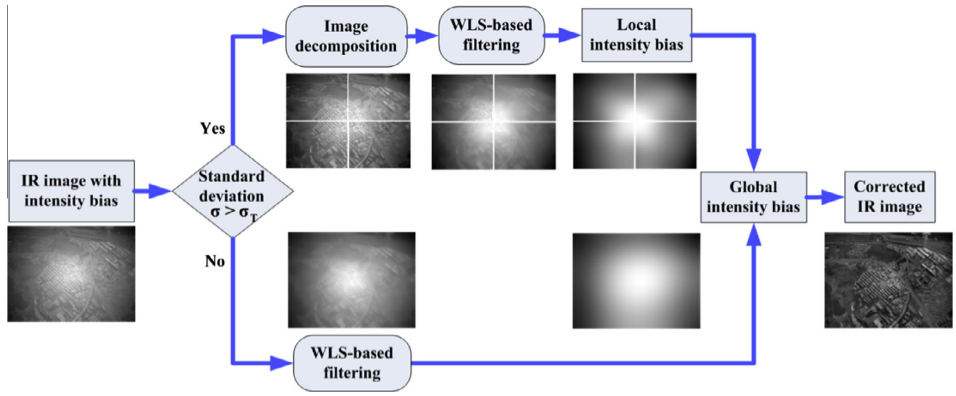

Fig. 1. Workflow of the proposed correction method.

image σ is larger than the threshold value σ_T, a patch-based correction model is used to estimate the local intensity bias fields, and finally all the local bias fields are merged into a global one. However, as σ is smaller than σ_T, the global intensity bias is directly estimated from the degraded image. Once intensity bias is well estimated, the corrected image can be easily obtained by subtracting it from the input image.

The remainder of this paper is organized as follows: In Section 2, we discuss the degradation model and automatic correction method. In Section 3, we present and analyze the experimental results. Finally, we summarize this paper in Section 4.

2. Automatic correction method

2.1. Degradation model

In this study, flight velocity does not exceed Mach 5, so the maximum flow temperature is not high enough to make the heated flow radiate. Therefore, aerothermal radiation mostly comes from the heated optical window. The simulation experiment of intensity nonuniformity is shown in Fig. 2. 2D temperature distribution of an IR optical window shown in Fig. 2(a) is computed using the finite-element-analysis code (ANSYS) as the aircraft flies at Mach 3 and flight altitude 4 km. The corresponding normalized irradiance distribution on the focal plane shown in Fig. 2(b) is obtained using ray tracing. Fig. 2(c) and (d) are an original IR image and a simulated aerothermal image, respectively. In Fig. 2, the aerothermal radiation received by the IR detector as one kind of additive background noise significantly lowers signal-to-noise ratio of an IR imaging system. And this effect has also been observed in a wind tunnel experiment. Image background intensities dramatically and unevenly increase with experimental time [6,7].

Thus, the image degradation model is expressed as

$$Z = S + B + n \tag{1}$$

where Z and S are the degraded aerothermal image and the sharp image, respectively, B denotes the aeroheating-induced intensity bias field, and n is system noise.

2.2. Correction method

To accurately estimate the intensity bias field B, an isotropic TV correction model is proposed and expressed as

$$E(B) = \min \|\nabla Z - \nabla B\|_2 \tag{2}$$

where ∇Z and ∇B represent the vector-form gradients of the aerothermal image and its bias, respectively, and $\|\cdot\|_2$ denotes the L_2-norm.

Our aim is to accurately estimate the additive intensity bias field B and then subtract it from the original aerothermal image Z. In [6,7], the intensity bias field B can be fitted accurately by using a multivariate polynomial. Thus, a K degree polynomial model is chosen to denote a 2D bias field, and it is expressed as

$$B(x_i, y_i) = \sum_{t=0}^{K}\sum_{s=0}^{K-t} a_{t,s} x_i^t y_i^s = W\mathbf{a} \tag{3}$$

where $\mathbf{a}$ is the column vector holding the model parameters $\{a_{t,s}\}$, and W is the row vectors holding the monomial terms.

In Eq. (2), ∇Z is obtained directly from the given image. For ∇B, the x component of ∇B can be expressed as

$$\nabla B_{x,i} = C_x \mathbf{a} = \begin{pmatrix} \partial W_1/\partial x \\ \cdots \\ \partial W_N/\partial x \end{pmatrix} \mathbf{a} \tag{4}$$

The y component of ∇B can be computed using the same method. Thus, we have the writing of Eq. (2):

$$E(\mathbf{a}) = \min \|\nabla Z - \mathbf{Ca}\|_2 \tag{5}$$

where $\mathbf{C} = [C_x; C_y]$ is a constant matrix.

Because of the influence of the gradient components of a manageable degree of low-amplitude structures and noise in the degraded image on the aforementioned minimization problem, the smoothing operator based on WLS optimization framework is applied. Formally, it can be expressed as

$$\hat{Z} = (\mathbf{I} + \lambda \mathbf{L})^{-1} Z \tag{6}$$

where $\mathbf{I}$ is the identity matrix, $\mathbf{L} = \mathbf{D}_h^T \mathbf{W}_h \mathbf{D}_h + \mathbf{D}_v^T \mathbf{W}_v \mathbf{D}_v$ with $\mathbf{D}_h$ and $\mathbf{D}_v$ being the horizontal and vertical gradient operators, respectively, and $\mathbf{W}_h$ and $\mathbf{W}_v$ are the smoothness weights which depend on Z. λ is the positive parameter.

Therefore, the modified model is expressed as

$$E(\mathbf{a}) = \min \|\nabla \hat{Z} - \mathbf{Ca}\|_2 \tag{7}$$

Using the half-quadratic penalty method [8], we now introduce an auxiliary variable $\mathbf{U} = \nabla \hat{Z} - \mathbf{Ca}$, and reformulate the problem in Eq. (7) as

$$E(\mathbf{a}, \mathbf{U}) = \min \frac{\beta}{2} \|\nabla \hat{Z} - \mathbf{Ca} - \mathbf{U}\|_2^2 + \|\mathbf{U}\|_2 \tag{8}$$

When $\beta \to \infty$, the above minimization problem would have the same solution as the problem in Eq. (7). Clearly, Eq. (8) is convex in $(\mathbf{a}, \mathbf{U})$. While either one of the two variables $\mathbf{a}$ and $\mathbf{U}$ is fixed, minimizing the function with respect to the other has a closed-form formula with low computational complexity and high numerical stability.Thus, we adopt an alternating minimization algorithm to