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Non-uniformity correction of infrared focal plane array in point target surveillance systems

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HIGHLIGHTS

- We analyze the effect of non-uniformity correction on point target detection.
- We propose a non-uniformity correction method for staring sensor.
- We propose a correction and filtering joint method for scanning sensor.
- It is noted that the non-uniformity and correction models still need more research.

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ABSTRACT

We discuss the influence of non-uniformity and non-uniformity correction on point target detection in infrared surveillance system, and propose a non-uniformity correction approach which is based on signal intensity and sensor characteristics. Theoretical models are used to derive the combined effect of background clutter, sensor random noise, target, non-uniformity and correction error on the signal-to-noise-and-clutter ratio. From our analysis, it can be noted that background clutter intensity is successively modulated by sensor non-uniformity and non-uniformity correction, while sensor random noise is modulated by the non-uniformity correction process only. Furthermore, background clutter and sensor random noise are the key factors that affect the performance of a surveillance system, when it is used to detect point targets. The method presented in this paper takes all of the above into account, moreover, it considers the difference between scanning and staring focal plane array. The experimental results demonstrate the effectiveness of the proposed method.

1. Introduction

Infrared focal plane array (IRFPA) is widely used in military and civil fields, however, infrared (IR) images can be severely degraded by fixed pattern noise (FPN) which is caused by the non-uniformity (NU) of the detector response. It is impossible that all detectors have an identical photoresponse, and this spatial non-uniformity of IRFPA produces a fixed noise pattern in every picture over short time-scales, because the FPN is also characterized by a very slow temporal drift [1] (this drift is not our focus in this paper). As an important method to reduce the FPN of FPA sensors, non-uniformity correction (NUC) is a key technology in the application of IRFPA. Most studies of NUC generally consist of three phases as follows:

(1) Modeling: the first is to build a model of non-uniformity.
(2) Parameters estimation: the next is to estimate parameters of the model.
(3) Correction: the last is to correct the output signals according to the non-uniformity model and the estimated parameters.

Traditionally, NUC techniques fall into two categories consisting of calibration-based and scene-based techniques [2]. Calibration-based techniques utilize an absolute temperature reference, such as a blackbody radiation source that is placed within the sensor field of view and is heated to one or more uniform and known temperatures, to estimate the gain and offset of each detector of the FPA [3,4]. Calibration-based techniques can provide reasonably good estimates of the non-uniformity, when parameter drift is negligible. While scene-based techniques typically use an image sequence and rely on motion or changes in the actual scene to perform NUC [5], and they focus on how to accurately estimate correction parameters over time [6–8].

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Most of these studies did not consider the impact of NUC on the detection performance of an infrared surveillance system, when it is used to detect point targets. However, the impact cannot be ignored in some cases.

The problem of point target detection is that most target information (such as shape, size, and texture) cannot be used for detection [9], and the gray level difference between target and background is usually the only available information. Therefore, the point target detection performance is strongly influenced by background clutter and sensor noise. On the other hand, both background clutter and point target are modulated by FPA non-uniformity and NUC, while sensor random noise is modulated by the correction process only. Thus, the effect of correction on the performance of point target detection should be discussed in detail. In order to obtain an optimal approach for dim point target detection, we focus on the combined effect of five factors (background clutter, target, sensor random noise, non-uniformity and residual error after non-uniformity correction) on the signal-to-noise-and-clutter ratio (*SNCR*). And then we analyze the adaptability of some traditional NUC methods, and finally we propose a new NUC method and the corresponding point target detection algorithm.

A series of simulation experiments are performed with the proposed method, and the experimental results demonstrate the good detection performance of our method of the point target surveillance system.

The remainder of this paper is organized as follows. In Section 2, we firstly discuss the signal model and the non-uniformity model. The correction error and the evaluation of NUC are also analyzed in this section. Then, we present the problem of NUC for point target surveillance system. In Section 3, we study the combined effect of the IRFPA non-uniformity, correction error, sensor random noise, target and background clutter on the performance of point target detection. Based on our analysis and the imaging characteristics of staring sensor, a corresponding NUC method is proposed. In Section 4, a joint method of NUC and filtering for scanning images is given. Simulation and experimental results are presented in Section 5. Our conclusion is given in Section 6 finally.

2. Description of the problem

2.1. Model of non-uniformity

Non-uniformity model of infrared image can be described as follows: assume y is the readout signal of IRFPA, x is the irradiance collected by the detector during the integration time, and the relationship between y and x can be characterized as a linear or nonlinear function $y(x)$. The linear response model can be expressed by the following equation [10–12]

$$y(x) = Ax + B + n \tag{1}$$

where A and B are the gain and offset of the detector respectively, and n is the additive noise.

If we consider a nonlinear model, the response curve of the detector can be divided into many parts each of which can be approximated by a straight line [8,13]. Complex models [14] are ignored in this paper.

Due to the difference of imaging mechanisms, the non-uniformity response models of staring and scanning imaging systems should be discussed respectively. The linear response model of scanning sensor is described as follows [7]:

$$y_{i,j}(x,t) = A_i x + B_i + n_{i,j}(t) \tag{2}$$

where $y_{i,j}(x, t)$ is the readout signal and $n_{i,j}(t)$ is the sensor noise of the (i,j) th pixel at time t, A_i and B_i are the gain and offset of the ith channel respectively. The additive noise $n_{i,j}(t)$ is usually a zero-mean Gaussian random variable with variance of σ^2 [6,15].

The linear response model of staring sensor can be expressed as [6,13,15]:

$$y_{i,j}(x,t) = A_{i,j}x + B_{i,j} + n_{i,j}(t) \tag{3}$$

where $A_{i,j}$ and $B_{i,j}$ are the gain and offset of the (i, j) th detector in IRPFA.

2.2. Signal model of surveillance system

If we ignore the non-uniformity in IRFPA, the read out signal $f$of the (i, j)th detector at time t can be expressed as the following equation [9,16]:

$$f_{i,j}(t) = S_{i,j}(t) + C_{i,j}(t) + N_{i,j}(t) \tag{4}$$

where $S_{i,j,t}$ is the target signal, $C_{i,j,t}$ is the background clutter signal and $N_{i,j,t}$ is the sensor noise. As the target is small enough, the collected radiation value x in Eqs. (2) and (3) can be expressed as a sum of background clutter and target:

$$x_{i,j}(t) = S_{i,j}(t) + C_{i,j}(t) \tag{5}$$

According to Eqs. (5), (2) and (3) can be rewritten as:

$$y_{i,j}(S,C,t) = A_i(S_{i,j}(t) + C_{i,j}(t)) + B_i + n_{i,j}(t) \tag{6}$$

$$y_{i,j}(S,C,t) = A_{i,j}(S_{i,j}(t) + C_{i,j}(t)) + B_{i,j} + n_{i,j}(t) \tag{7}$$

where

$$S_{i,j}(t) = \begin{cases} s & \text{the target is present at time } t \\ 0 & \text{the target is not present at time } t \end{cases}$$

and s denotes the target signal value.

2.3. Model of non-uniformity correction

Scene-based NUC techniques are not suitable for the point target detection system, because the correction relies on the changes in the actual scene, and the detection always depends on the dim point target moving in a relatively static scene. Calibration-based techniques are more suitable for the point target surveillance system, and these techniques include one-point correction, two-point correction and multi-point correction [17]. Multi-point correction is actually a modified method of two-point correction, so our work focuses on one-point and two-point correction.

(1) One-point correction

The output signal after one-point correction can be written as:

$$z(x,t) = y(x,t) - (y(X_1,t_1) - \overline{y(X_1,t_1)}) \tag{8}$$

where X_1 is the radiation received by the detector when the sensor is calibrated with the calibration temperature T_1 at time t_1. $y(X_1,t_1)$ is the output of the detector during the calibration procedure, and $\overline{y(X_1,t_1)}$ is the average of $y(X_1,t_1)$. For convenience, the indexes i and j are omitted.

Ignoring sensor noise, Eq.(8) can be rewritten as:

$$\begin{aligned} z(x) &= Ax + B - (AX_1 + B - \overline{(AX_1 + B)}) \\ &= A(x - X_1) + \overline{A}X_1 + \overline{B} = Ax' + B' \end{aligned} \tag{9}$$

where $(x - X_1) = x'$, $\overline{A}X_1 + \overline{B} = B'$, and $\overline{A}$ is the average of A, and $\overline{B}$ is the average of B.

From Eq. (9), the response curves of all detectors are offset-compensated after one-point correction, as shown in Fig. 1.