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Scale-space point spread function based framework to boost infrared target detection algorithms

Saed Moradi, Payman Moallem *, Mohamad Farzan Sabahi

Department of Electrical Engineering, Faculty of Engineering, University of Isfahan, Isfahan, Iran

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A B S T R A C T

Small target detection is one of the major concern in the development of infrared surveillance systems. Detection algorithms based on Gaussian target modeling have attracted most attention from researchers in this field. However, the lack of accurate target modeling limits the performance of this type of infrared small target detection algorithms. In this paper, signal to clutter ratio (SCR) improvement mechanism based on the matched filter is described in detail and effect of Point Spread Function (PSF) on the intensity and spatial distribution of the target pixels is clarified comprehensively. In the following, a new parametric model for small infrared targets is developed based on the PSF of imaging system which can be considered as a matched filter. Based on this model, a new framework to boost model-based infrared target detection algorithms is presented. In order to show the performance of this new framework, the proposed model is adopted in Laplacian scale-space algorithms which is a well-known algorithm in the small infrared target detection field. Simulation results show that the proposed framework has better detection performance in comparison with the Gaussian one and improves the overall performance of IRST system. By analyzing the performance of the proposed algorithm based on this new framework in a quantitative manner, this new framework shows at least 20% improvement in the output SCR values in comparison with Laplacian of Gaussian (LoG) algorithm.

1. Introduction

Recent development of high performance infrared detectors makes a great opportunity for infrared search and track systems (IRST) to have decisive role in defense industries and military applications. Identifying locations of incoming unknown threats like as high-speed aircrafts and missiles is the most application of the IRST system [1].

In order to have enough time to defeat enemy threats, IRST systems should have long-distance target identifying capability. However, distant infrared target detection faces challenges as:

- Small infrared targets have very low contrast and inferior signal to noise ratio (SNR) [2].
- Due to atmospheric effects, the edge of small infrared target is dimmed. Thus, edge detection for small infrared target faces difficulty [3].
- Cloud edge and sun glint have similar properties to real targets. These natural phenomena create heavily cluttered background in aerial and naval infrared images [4].
- Different source of noises reduce the quality of the output infrared image [5].
- To achieve real-time processing, target detection algorithm should have low computational complexity [6].

Detection and false alarm rate, are the main metrics in evaluating the performance of an IRST system. Detection rate which determines the sensitivity of the IRST system, measures the proportion of real targets which are correctly identified. False alarm rate or specificity, is defined as proportion false alarms that incorrectly classified as real targets. These two metrics are closely related to the output signal to clutter ratio (SCR) which is defined as:

$$\mathrm{SCR} = \frac{f_T - f_B}{\sigma_B} \tag{1}$$

where f_B and σ_B denote mean and standard deviation of local background, respectively. f_T represents maximum value of target region [7]. Higher SCR value in filtered image leads to higher detection rate and lower false alarms, obviously. In the other words, long-distance

* Corresponding author.
E-mail address: p_moallem@eng.ui.ac.ir (P. Moallem).

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incoming targets with low SNR have more possibility to be detected and maximum detection range of overall IRST system is improved. Also, lower false alarm rate can be achieved without missing real targets. Thus, by increasing output SCR, the main specifications of IRST system are improved simultaneously.

There are too many researches that dedicated to infrared small and pointwise target detection in the literature which are proposed to improve SCR in filtered image. The target detection algorithms comprise two main approaches. In background suppressing approach, the background is estimated based on spatial and temporal correlation of neighborhood pixels. Then, the estimated background is subtracted from original image, and the target candidate points are extracted. This approach has real-time implementation ability and seems proper for utilizing in practical systems. However, using this approach in real scenarios with heavily cluttered background leads to high false alarm rate [8].

The other approach, directly improve the targets and eliminate the background, simultaneously. In this approach, detection algorithm is developed based on predefined small infrared target model. In all methods which use this approach, the spatial distribution of the small targets are approximated using 2-D Gaussian function. Authors in [9] present an infrared target detection algorithm based on human visual system (HVS) that results in small infrared targets can be modeled using Gaussian distribution and scale-space representation is used for detection of variable-size targets. A target detection algorithm based on self-information map (SIM) is presented in [10]. The SIM is integrated with adaptive thresholding and region growing technique is applied in the next step. Adaptive high-pass filter is used in [11] to detect infrared targets in IRST systems. A temporal–spatial algorithm is proposed in [12] for detecting naval infrared targets. The authors used a three plot correlation filter and statistics-based clutter rejection. Character filter is another Gaussian-based target detection algorithm [13]. An evaluation metric called 'shape parameter' is used to categorize infrared image pixels into target, background and noise categories and extract targets directly. The combination of bilateral filter and temporal cross product is proposed in [14]. Authors in [2] proposed an improved template matching algorithm for IRST systems. Unlike conventional template matching, the projection coefficients obtained from principal component analysis are adopted as templates. Also, the authors proposed a nonlinear correlation as similarity measure. Tune-max process is applied over several scales in [15] to maximize signal to clutter ratio (SCR) for incoming small target in infrared images.

The above mentioned algorithms use 2-D Gaussian model as an approximated spatial distribution for small targets and have good performance and capability in target detection when Gaussian assumption for target shape and distribution is acceptable. However, at some conditions in reality, Gaussian assumption is rather rough approximation of the infrared targets [16]. Furthermore, geometrical and optical specifications of infrared imaging systems affect the resulting image on the image plane [17]. Hence, the gray level intensity and spatial distribution of image of the small target may have non-Gaussian distribution. Here, these questions are raised:

1. Which parameters affect the spatial distribution of infrared target pixels?
2. How precise target modeling improves detection performance?

The main contributions of this paper is to answer the above-mentioned questions.

In this paper, a novel framework for detection of infrared targets is introduced which can be applied to all model-based algorithms. The proposed framework, which its primary version was presented in ICDIP'14 conference [18], is based on intrinsic optical characteristic of the infrared image acquisition system. Here, Point Spread Function (PSF) is adopted for small infrared target modeling. Since PSF of an optical system has a prominent impact on gray level intensity and area occupied by small point target in infrared images, using the proposed target modeling leads to robust and accurate performance in targets detection.

The rest of this paper is organized as follows: in the next section, SCR improvement mechanism and affecting factors on the intensity of the target pixels are described comprehensively. Matched filtering as SCR improvement mechanism and PSF as a factor affect target spatial distribution, are explained. The Section 3 is dedicated to the principle of the proposed framework. In this section a parametric model is developed for small infrared targets and a new framework is presented to boost model-based target detection algorithms. Simulation results are given in the Section 4, and finally, the paper is concluded in the Section 5.

2. SCR improvement mechanism and affecting factors on the target pixels intensity

In order to answer the questions which were posed in the introduction, in this section, the principles of the matched filter, which plays major role in detection theory, is explained. Having knowledge about SCR improvement mechanism will aid efficacious detection algorithm design. Then, point spread function which directly affects gray level and spatial distribution of the infrared targets, is described. With prior information about target shape and intensity, detection algorithms could be designed in smart way.

2.1. Matched filters

Assume that we want to detect arbitrary 1-D signal $x(t)$ in presence of additive white Gaussian noise $n(t)$ (Fig. 1). If the noisy signal $v_{in}(t) = x(t) + n(t)$ passes through a filter whose transfer function is $H(f)$, the output signal $v_{out}(t)$ can be expressed by:

$$v_{out}(t) = \int H(f)V_{in}(f)e^{j2\pi ft}df = \int H(f)\{X(f) + N(f)\}e^{j2\pi ft}df \qquad (2)$$

where $N(f)$ is the noise spectrum and, $X(f)$ and $V_{in}(f)$ are Fourier transform of $x(t)$ and $v_{in}(t)$, respectively. In order to achieve the best detection performance, the filter should be design in a way, to achieve maximum output signal to noise ratio (SNR). It has been proven [19] that the transfer function of the optimum filter ($H_{opt}(f)$) which maximizes the SNR, is:

$$H_{opt}(f) = X^*(f) \qquad (3)$$

where $X^*(f)$ represents the conjugate Fourier transform of $x(t)$. If $x(t)$ is assumed to be a real signal, the impulse response of the optimum filter ($h_{opt}(t)$), is:

$$h_{opt}(t) = x(-t) \qquad (4)$$

The optimum filter $h_{opt}(t)$ is called the matched filter for the signal $x(t)$. Note that, if input signal is symmetric around Y-axis (for 1-D signals) or isotropic (for 2-D signals), the impulse response of the optimum filter is equal to the input signal [20]. Hence, the best filter for detecting infrared small targets has as the same gray level and spatial distribution as the target.

2.2. Point spread function

An incoming infrared target can be considered as point source, when it is far enough from imaging system. A point source represented as single pixel in the ideal image but it spreads out in real images (Fig. 2). This phenomenon has two main reasons: (1) the