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Joint detection and tracking of size-varying infrared targets based on block-wise sparse decomposition

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HIGHLIGHTS

- Detection and tracking of size-varying targets is a great challenge task.
- A joint detection and tracking method for size-varying targets is proposed.
- The method provides higher detection performance using more target information.
- The motion direction extracted from extent is used to improve tracking performance.

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ABSTRACT

The high variability of target size makes small target detection in Infrared Search and Track (IRST) a challenging task. A joint detection and tracking method based on block-wise sparse decomposition is proposed to address this problem. For detection, the infrared image is divided into overlapped blocks, and each block is weighted on the local image complexity and target existence probabilities. Target-background decomposition is solved by block-wise inexact augmented Lagrange multipliers. For tracking, label multi-Bernoulli (LMB) tracker tracks multiple targets taking the result of single-frame detection as input, and provides corresponding target existence probabilities for detection. Unlike fixed-size methods, the proposed method can accommodate size-varying targets, due to no special assumption for the size and shape of small targets. Because of exact decomposition, classical target measurements are extended and additional direction information is provided to improve tracking performance. The experimental results show that the proposed method can effectively suppress background clutters, detect and track size-varying targets in infrared images.

1. Introduction

Infrared Search and Track (IRST) has been applied to many military or civil fields such as precise guidance, early warning, space situation awareness (SSA), video surveillance, and so on [1–7]. As a key technique, small target detection plays an important role in IRST. Especially, the single-frame detection methods can better satisfy the real-time requirement, and is widely used in practical IRST systems. However, infrared targets have special characteristics. For example, the size of infrared target may be dynamic, and such targets are called as size-varying small targets. The phenomenon makes the detection quite difficult. In this paper, we investigate the problem of joint detection and tracking size-varying infrared small targets by block-wise sparse decomposition.

Generally, infrared small target is modeled as 2D Gauss model [8–10]. It assumes that the target is at far distance and close to a point source. However, the 2D Gauss model cannot cover all targets in practical applications. For example, target projection in infrared focal plane array may change due to distribution of radiant intensity, imaging distance, optic angle of sensor, atmosphere environments, and so on [11]. The high variability of target projection makes target detection and tracking a challenging task, especially when there are heavy clutters in the background.

Conventional infrared small target detection methods, such as mean subtraction filter [12], median subtraction filter [13], TopHat filter [14], MaxMean/MaxMedian filter [15], least mean square filter [16] and matched filter [17], were designed for fixed-size targets. Although those methods can somewhat suppression the background clutters, they cannot accommodate size-varying targets. In terms of the matched filter theory, the fixed-size filters can effectively detect targets only when the assumed target sizes

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match the ground truth. Unmatched sizes will result in the performance degradation of background suppression, and then the probability of false alarms and missed targets will increase rapidly. Thus, the performance of conventional fixed-size methods is limited for size-varying targets. Recently, many researchers have paid attention to the detection of size-varying small targets. Philip proposed a local contrast method (LCM) for infrared target detection [18]. The method is inspired by the contrast mechanism of human vision system, and use LCM to measure the dissimilarity between the current location and its neighborhoods. Kim proposed Tune-Max of SCR (TM-SCR) method using Laplacian scale-space theory and an optimization method [11]. However, LCM and TM-SCR were designed strictly based on 2D Gauss target model and cannot accommodate targets with arbitrary shapes.

Nowadays, Robust Principal Component Analysis (RPCA) has attracted many research interests from signal/image processing communities [19–23]. In certain condition, a matrix can be decomposed into a low-rank matrix and a sparse matrix based on the theory. The decomposition processing has no special assumption for the size and shape of sparse components, so RPCA has a great advantage for infrared small target detection. Recently, Zheng, Gao and Wang has proposed their detection methods based on RPCA respectively [10,24,25]. They constructed different observation matrix and used traditional RPCA to realize low-rank and sparse matrix decomposition. Although great progress has been made, complex background clutters cannot be effectively suppressed in their methods, which is a great obstacle for practical applications.

To robustly detect size-varying small targets in single-frame infrared image, we propose a joint detection and tracking method based on block-wise sparse decomposition. In our method, infrared image is divided into overlapped blocks, and is decomposed into low-rank components and sparse components with adaptive weighting parameters of different blocks. The adaptive weighting parameter of each block is calculated based on local image complexity and target existence probabilities. The target existence probabilities are provided by labeled multi-Bernoulli (LMB) tracker [26]. In turn, block-wise sparse decomposition gives more target information to the LMB tracker and improves the tracking performance. The experimental results indicate that the proposed method outperforms other baseline methods in the term of background suppression, target detection and target tracking.

The rest of the paper is organized as follows: Section 2 introduces the model of infrared image and the LMB tracker. Section 3 proposed the block-wise sparse decomposition. The calculation of adaptive weighting parameters and the solution of block-wise sparse decomposition are also given. Section 4 provides the complete joint detection and tracking method. The overall performance of the proposed method and comparison results with other methods are presented in Section 5. Finally, conclusions are drawn in Section 6.

2. Background

This section introduces briefly the infrared image model and LMB tracker necessary for the results of this paper. For additional details, the reader is referred to references [24,26,27].

2.1. Infrared image model

Generally, single infrared image can be modeled as [10,28]:

$$D(x,y) = T(x,y) + B(x,y) + N(x,y), \tag{1}$$

where $D, T, B, N, (x,y)$ are the original infrared image, the target image, the background image, the random noise and the pixel location, respectively. Based on RPCA theory, the infrared image can also be modeled as $M = L + S$, where M, L and S represent observation matrix (original image), low-rank matrix (background) and sparse matrix (targets), respectively.

For infrared small targets, in practical applications, the target size may keep changing all the time. However, it is small with respect to the whole infrared image. Thus, the sparse assumption is reasonable for infrared small targets, and S can be considered as a sparse matrix, i.e.

$$\|S\|_0 < k, \tag{2}$$

where $\|\cdot\|_0$ represents the $l0$ norm which counts the number of nonzero entries, and k is dependent on the number of small targets and their sizes. It's apparent that k is far less than the number of pixels of the whole infrared image. In other words, most of the entries of the matrix S are zero [10].

Background in infrared image can be considered as a low-rank matrix, i.e.

$$rank(L) \leqslant r, \tag{3}$$

where r indicates the complexity of the background image. The value of r is larger for the complex background than for the smooth background.

2.2. Labeled multi-Bernoulli tracker

In our method, target existence probabilities are used to compute weighting parameter for target regions. Thus, multi-target tracker is needed. A recent approach of multi-target tracking is to represent the multi-target state as a labeled multi-Bernoulli random finite sets (RFS). A multi-Bernoulli RFS X can be regarded as a union of independent Bernoulli RFSs, i.e. $X = \{x^{(\ell)}\}_{\ell\in\mathbb{L}}$. The single target state is the position and velocity vector, i.e. $x = (p_x, v_x, p_y, v_y)$. The term $\mathbb{L}$ denotes the label space. Single target state is described by target existence probability r and spatial distribution p. Then, a labeled multi-Bernoulli RFS can be represented by parameter set $\{r^{(\ell)}, p^{(\ell)}\}_{\ell\in\mathbb{L}}$. Classical LMB tracker is performed on 2D point measurement set after threshold segmentation, i.e. $Z = \{z^{(i)}\}_{i=1}^{M}$. Only position information is available, i.e. $z = (p_x, p_y)$. The labeled multi-Bernoulli recursion is achieved by prediction step and update step. Prediction and update are carried out based on target transition function $f = (x|\cdot)$ and measurement likelihood function $g = (z|x)$, respectively. A target can be declared present if the target existence probability r is greater than certain threshold. The threshold is usually set to 0.5.

3. Block-wise sparse decomposition

3.1. Formulation of block-wise sparse decomposition

Low-rank and sparse matrix decomposition can be carried out via traditional RPCA, as [24]:

$$\min_{L,S} \|L\|_* + \lambda\|S\|_0 \ s.t.\ M = L + S, \tag{4}$$

where $\|\cdot\|_*$ indicates the nuclear norm of a matrix. λ is an weighting parameter, which trades off the low-rank and sparseness. When the value of λ is large, more entries of observation matrix are classified as background, and it enhances background suppression. On the contrary, when the value of λ is small, more entries are classified as targets.

Block-wise sparse decomposition for single-frame image is proposed and can be expressed as Eq. (5), when blocks are not allowed overlapping.