ADAPTIVE BACKGROUND REMOVAL FOR THE DETECTION OF DIM TARGETS IN INFRARED SURVEILLANCE SYSTEMS

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ABSTRACT

In this work we propose an adaptive procedure to initialize the spatial filter for the removal of the clutter from scenarios typical of Infra-Red (IR) surveillance systems. The effectiveness of the proposed method is investigated by means of simulation tests on real IR data representing a maritime scenario. The results are compared with the ones achieved by the classical configurations of the spatial filters employed for the background clutter estimation.

Keywords: target detection; background removal; IR surveillance systems.

1. INTRODUCTION

A typical application of IR surveillance systems is the detection of small moving targets. In military applications, IR systems can support radar sensors bringing two main advantages to the detection system. First, IR technologies employ passive sensors thus nullifying electro-magnetic countermeasures (EMC). Additionally, in applications such as maritime surveillance, the performances of IR systems are not affected by the multi-path phenomenon. Generally, IR systems are effectively employed in the detection of moving targets which are located at long distances and are characterized by a small spatial extent and a very low signal-to-clutter ratio (SCR).

A well-established scheme to perform target detection is composed of two cascaded stages. The first pre-processing step provides the estimation and removal of the background clutter in order to simplify the detection strategies. In the second step, detection over the residual clutter is performed. Classical techniques for the removal of the background clutter use a spatially moving window and are often characterized by low performances in the regions of edges, for example the separation-line between sea and sky or the edges between sky and clouds. These are two typical examples of regions where in the real operating scenario the target could be characterized by a small SCR thus making the detection very difficult.

The algorithm discussed in this paper, is characterized by a novel initialization step for the purpose of setting some critical parameters of the spatial filter according to the processed scene and to the size of the target to detect. The whole algorithm and the initialization step are described in Section II. The results are discussed in Section III by using a set of experimental IR data.

2. DESCRIPTION OF THE ALGORITHM

We consider images composed by $M$ rows and $N$ columns. The generic pixel $s[i,j]$, having spatial coordinates $i$ and $j$, is modeled as in the following equation:

$$s[i,j] = t[i,j] + b[i,j] + n[i,j]$$

(1)

where $n[i,j]$ is the noise term (thermal noise, photon noise, fixed pattern noise) assumed as a zero-mean Gaussian random variable, $b[i,j]$ is the spatially non-stationary background. $t[i,j]$ is the target signal and can be written as:

$$t[i,j] = A_s s_i[i - i_o, j - j_o]$$

(2)

where $s_i(i,j)$ is the normalized target signal centered in the spatial coordinates $i_o, j_o$ and $A_s$ is the target peak value.

Since we are interested in the detection of dim targets, it is reasonable to assume that the spatial extension of $s_i(i,j)$ is comparable to that of the sensor point spread function (PSF). Moreover, in the applications of interest the target amplitude $A$ is very low if compared to the signal of the clutter. Hence, the detection problem has to be accomplished with low values of SCR which is defined as in [1]:

$$SCR = \frac{A^2}{\sigma_{\text{b+p}}}$$

(3)

where with $\sigma_{\text{b+p}}$ we indicate the variance of background-plus-noise signal. As shown in Figure 1, the algorithm consists of three distinct steps: 1) initialization of the
background removal (BR) filter parameters, 2) background estimation and removal, 3) detection over the residual clutter. Each step is introduced in the following subsections.

2.1 Initialization of the BR spatial filter

We propose a novel initialization step for the purpose of correctly estimating the background clutter. The parameters that characterize the BR spatial filter have to be properly determined in order to improve the performances of the detection algorithm. Only a few frames have to be acquired to efficiently initialize the spatial filter. Low-SCR targets are randomly simulated in proximity of the most prominent edges of the scene, i.e. in regions where detection cannot be easily accomplished. Then, the estimation of the background is operated by varying the parameters of the spatial filter employed (i.e. the dimension of the mask, standard deviation of the Gaussian filter).

Setting a fixed fraction of detected targets (FoDT), we choose the dimensions of the spatial filter in correspondence of the minimum false alarm rate (FAR) achieved, i.e.

\[
\min_{N_{\text{mask}}, M_{\text{mask}}} \text{FAR}(N_{\text{mask}}, M_{\text{mask}}),
\]

where \(N_{\text{mask}}\) and \(M_{\text{mask}}\) are respectively the vertical and horizontal dimension of the spatial filter’s mask, \(N_{\text{mask, opt}}\) and \(M_{\text{mask, opt}}\) are the related optimal parameters obtained from the initialization step. It is worth noting that a compromise has to be reached between the parameters of the spatial filter that minimize the FAR and the required computational cost which is commonly considered a critical aspect of real-time IR applications. Directly referring to the median filter, we use this novel procedure to set the horizontal and vertical dimensions of the mask that best suits to the characteristics of the processed scene.

2.2 Clutter estimation and removal

In IR detection systems the clutter removal procedure is introduced for the purpose of achieving two important aims:

- the preservation of the target SCR in order to leave the FoDT unchanged;
- global reduction of the background structures to reduce the FAR.

One of the most effective methods to estimate the background employs the median filter which belongs to the family of ranked order filters. Such filters replace the intensity value of a given pixel with another intensity value selected in a window surrounding it. The values in the window are sorted in ascending order and, in the case of the median filter, the selected value is the central one. The median filter is characterized by two important properties [4]:

- the background estimation can be accomplished preserving the edge-structures of the scene;
- the median filter is robust to impulse signals thus target leakage can be limited.

Hence, the signal obtained from the removal of the background clutter can be expressed as:

\[
y_{ij} = s_{ij} - \hat{b}_{ij} = t_{ij} + r_{ij} + n_{ij} = t_{ij} + g_{ij}
\]

where \(\hat{b}_{ij}\) and \(r_{ij}\) are respectively the clutter estimate and the residual clutter obtained after the spatial filtering. Hereinafter, since the terms \(r_{ij}\) and \(n_{ij}\) in (4) can be considered statistically independent [2, 3], we regard them as a single term denoted as \(g_{ij}\).

2.3 Detection algorithm

From equation (4), the detection problem can be formulated as a binary test decision:

\[
H_0: y_{ij} = g_{ij}
\]

\[
H_1: y_{ij} = A \sigma_s (\tilde{l}_{ij} - t_{ij} - j_{ij}) + g_{ij}
\]

where \(g_{ij}\) is a Gaussian random process with zero mean and unknown covariance matrix. In order to evaluate the performances of the background removal, we have performed detection over the signal-plus-noise images by means of a classical detection algorithm [1]. Such algorithm is derived by the assumption that clutter is locally Gaussian [3]. The decision test is explained in equation (6):

\[
\tilde{H}(y) = \begin{cases} 
H_1: y_{ij} \text{ is a target pixel} \\
H_0: y_{ij} \text{ is a background pixel}
\end{cases}
\]

\[
T(y_{ij}) = \frac{y_{ij} - \hat{\mu}_s}{\bar{\sigma}_s} > \lambda
\]

where \(y_{ij}\) is the pixel under test after background removal, \(T(y_{ij})\) is the detection statistic, \(\hat{\mu}_s\) and \(\bar{\sigma}_s\) are respectively
the estimates of the local mean and standard deviation of the residual clutter process, $\lambda$ is a fixed threshold.

3. EXPERIMENTAL RESULTS

We have investigated the performances of the algorithm by means of an experimental sequence of IR images recorded in a typical maritime scenario. The sequence is composed by $2 \times 10^3$ frames of dimension $284 \times 387$ pixels acquired by an IR sensor in the spectral window $3 - 5 \mu$m (middle-wave IR). The frames represent a typical operating scenario for IR surveillance systems on board of Navy ships. The performance of the system was tested via simulation. Synthetic targets were generated across the edge of separation between sea and sky for the purpose of reproducing the typical operating conditions. The targets were simulated as discrete Gaussian functions with unit variance, in order to simulate the PSF of the optical system. The amplitude $A_t$ of the targets were simulated according to the desired value of SCR, estimating the local statistics of mean value and standard deviation related to neighbors on the same line, due to the particular characteristic of the acquired scene. In Figure 2, we report a graph that refers to the initialization step of the dimension of the mask of the median filter. We can easily notice that the minimum value of the FAR is obtained in correspondence of a filter mask with dimensions of $1 \times 13$ pixels, hence a 1-D mask that separately processes the lines of the acquired scene. This is a reasonable result if we consider the characteristics of the processed scene. In fact, in the analyzed maritime scenario the detection problem is made difficult by the presence of the strong separation edge between sea and sky where we can find located the long-range targets of interest.

To confirm the initialization of the spatial filter, we investigated the results by means of ROC curves. In Figure 3(a), we report the curves representing FoDT versus FAR, setting SCR=16 dB. If we compare the two ROC curves related to detection tests operated with different dimensions of the median filter, i.e. $1 \times 13$ versus $7 \times 13$ pixels, it is worth noting that an appropriate setting of the spatial filter’s dimensions can produce a gain in FoDT up to 20% at FAR=$10^{-4}$. Another example of such experimental ROC is shown in Figure 3(b) where the FoDT is obtained by varying the SCR of the simulated targets. The threshold $\lambda$ was set so as to obtain FAR=$10^{-4}$. The figure shows that for SCR lower than 23 dB the median filter initialized with the proper dimensions clearly outperforms the detection algorithm with a median filter initialized with a sub-optimal choice of the mask’s dimensions. Namely, the optimal choice gains about 6-7 dB for percentages of FoDT in the range of $10\% - 90\%$.

4. CONCLUSIONS

In this paper, we have proposed a novel strategy for the initialization of the median filter employed in the estimation of the background clutter in a maritime surveillance scenario. Such initialization step aims at setting the dimensions of the median filter employed in the background estimation for the purpose of assuring high performances to the cascaded detection algorithm. The performances have been discussed in terms of ROC curves. The results have shown that the initialization step can improve the performances of the detection algorithm.

5. REFERENCES