Defence Science Journal, Vol. 61, No. 3, May 2011, pp.251-256, DOI: 10.14429/dsj.61.60

Performance Assessment of Pre-processing Filters for Infrared Search and Track Applications

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ABSTRACT

To enhance detection probability and to reduce false alarms, infrared imagery is pre-processed before subjecting it to detection algorithms in infrared search and track systems. Pre-processing algorithms are used to predict the complex background and then to subtract the predicted background from the original image. The difference image is passed to the detection algorithm to further distinguish between the target and the background and/ or noise more accurately. A number of pre-processing algorithms have been reported in literature, with their relative advantages and disadvantages. This paper brings out the computational complexities and simulation results of various algorithms for assessing their relative performances. Based on these parameters, statistical algorithms in general and max-min algorithms in particular, are recommended to be used for infrared search and track systems.

Keywords: Contrast sensitivity, point targets, pre-processing algorithms, infrared search and track, morphological filters, statistical filters, statistical algorithms, max-min algorithms, small target detection, false alarms, post-processing algorithms

1. INTRODUCTION

The detection of small moving targets in clutter is an important subject in the area of signal/image processing. The algorithms for the detection of small and point targets are fundamental part of infra-red search and track (IRST) system and play vital role in the success of such systems. Typically, the spatial pre-processing step is performed on the input image to predict the background, and consequently enhance the signal-to-clutter ratio (SCR). The detection algorithm may result in many false targets and this requires using the post-processing algorithms to reduce the false alarms. Pre-processing algorithms are used to predict the complex background and then to subtract the predicted background from the original image. The difference image is passed to the detection algorithm to further distinguish between the target and the background and/or noise more accurately. The aim is to fit the background as closely as possible in the original image without diminishing the target signal. Many pre-processing algorithms have been reported in the literature[1]. It has experimentally been verified that the detection of dim point size targets in cluttered background is not possible without increasing the signal-to-clutter plus noise ratio (SCNR) by pre-processing of IR data. The output of pre-processing algorithm is passed to the detection algorithm which actually detects the targets and it may result in many false targets and this may require using the post-processing algorithms to reduce false alarms and to generate candidate target list. The block diagram of the image processing algorithms for detection of point and/or small targets is given in Fig. 1.

2. PRE-PROCESSING FILTERS

The pre-processing algorithms can be broadly classified as morphological and statistical filters[1].

2.1 Morphological Filters

Morphological filters are based on successive use of erosion and dilation operations using a structuring element. Mathematical morphology provides an approach to the processing of images which is based on shape. The morphological operations tend to simplify image data, preserving their essential shape characteristics and eliminating

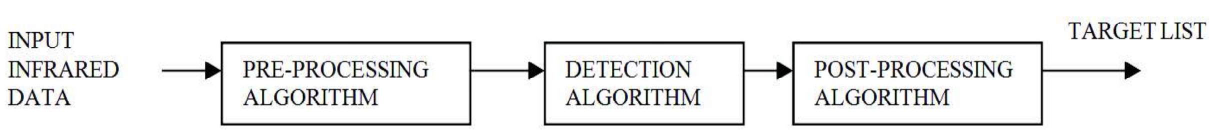

Figure 1. Block diagram of point and/or small target detection algorithms.

Received 11 March 2010, revised 4 February 2011, published online 26 April 2011

irrelevances. Opening process (erosion of image by structuring element, followed by dilation of the result by the same structuring element) eliminates bridges (narrow edge like set of pixels) connecting two regions of the image. It rounds outward-pointing corners in the image while leaving the inward-pointing corners unaffected. The closing process (dilation of image by structuring element, followed by erosion of the result by the same structuring element) rounds the inward-pointing corners in the image while leaving the outward corners unaffected. The problem with morphological filters is that the result is highly dependent on size and shape of the structuring element. The adaptive selection of size and shape of structuring element is a challenging task.

The gray-scale morphological operations can be defined as follows:

Let $f(x)$ and $g(x)$ be 1-D gray-scale functions of coordinate x, where $f(x)$ is the image and $g(x)$ is the structuring element. Let E represents Euclidean space, and, $F, G \subseteq E^2$. Then, $f: F \rightarrow E$ and $g: G \rightarrow E$, and the basic gray-scale dilation, erosion, closing and opening operations are defined in Eqns (1), (2), (3), and (4), respectively.

$$D_g(f) = \max[f(x-z) + g(z)], \quad \forall z \in G \text{, and } x - z \in F \quad (1)$$

$$E_g(f) = \min[f(x+z) - g(z)], \quad \forall z \in G \text{, and } x + z \in F \quad (2)$$

$$O_g(f) = (f \circ g) \bullet g(x) \quad (3)$$

$$C_g(f) = (f \bullet g) \circ g(x) \quad (4)$$

The computational load for some of the common composite morphological filters is shown in Table 1. The composite morphological pre-processing filters (in reference to Sr. Nos. 1, 2, 3 and 4 of the Table 1) used for simulation are defined by the Eqns (5), (6), (7), and (8), respectively. The Selective-Morpho CO_OC is computed similar to Morpho CO_OC filter with the difference that only alternate elements of the structuring elements are considered for processing.

$$Morpho\ C\_O = Mean\left(C_g(f), O_g(f)\right) \quad (5)$$

$$Morpho\ CO\_OC = Mean\left(C_g\left(O_g(f)\right), O_g\left(C_g(f)\right)\right) \quad (6)$$

$$Morpho\ COC\_OCO = Mean\begin{pmatrix} C_g\left(O_g\left(C_g(f)\right)\right), \\ O_g\left(C_g\left(O_g(f)\right)\right) \end{pmatrix} \quad (7)$$

Table 1. Computational complexity of morphological filters

Pre-processing filter	Operations/pixel*	Complexity
Morpho C_O	96	O(n^2)
Morpho CO_OC	192	O(n^2)
Morpho COC_OCO	288	O(n^2)
Morpho ECOC_DOCO	336	O(n^2)
Selective-Morpho CO_OC	112	O(n^2)

*Operations/pixels calculation is based on window size of 5x5

$$Morpho\ ECOC\_DOCO = Mean\begin{pmatrix} E_g\left[C_g\left(O_g\left(C_g(f)\right)\right)\right], \\ D_g\left[O_g\left(C_g\left(O_g(f)\right)\right)\right] \end{pmatrix} \quad (8)$$

2.2 Statistical Filters

Statistical filters are based on the fact that the statistical behaviour of the target and the background are not identical to predict the background. Filters like mean, median, max-median, max-min, mean median, selective median, 2-D Gaussian etc.[2-7]. The methodology here is to replace the background pixel by mean/median, etc. of the neighborhood. This assumes that one odd pixel occupied by the target (with higher intensity than the background) will not affect the statistics drastically.

The computational loads of some of the common statistical pre-processing filters are shown in Table 2.

3. SIMULATION METHODOLOGY

This study aims to find out a filter that is consistent and gives good performance, which can be used in the detection process. Towards this end, clouds were simulated using standard software program. Targets with known intensity and statistics were embedded in these video sequences.

The challenge is to decide a parameter for comparative analysis. The generally accepted parameter for this is the change in signal-to-noise ratio (SCNR). However, as brought out later in the paper, no clear-cut direction could be found based on this parameter. Next, we tried contrast sensitivity analysis. The ratio of the output contrast sensitivity to the input contrast sensitivity provided a good direction for selection of the pre-processing filter.

SCNR[8] is defined as given in the following equation:

$$SCNR(dB) = 10\log\left(\frac{(S_{\max} - \mu}{\sigma^2}\right) \quad (9)$$

where, $S_{\max}$ is the signal peak value, μ is the mean, and σ is the standard deviation of the background.

The contrast sensitivity, also known as Weber's fraction, is proposed to be the parameter for deciding the efficacy of pre-processing filters. Contrast sensitivity[9] is defined as given in Eqn (10).

Table 2. Computational complexity of statistical filters

Pre-processing filter	Operations/pixel*	Complexity
Median	625	O(n^2)
Max-Median	103	O(n)
Max-Min	19	O(n)
Mean-Median	105	O(n)
Gaussian	49†	O(n^2)
Mean	25	O(n^2)
Selective-Median	225	O(n^2)

*Operations/pixels calculation is based on window size of 5x5
†Size of the filter 5x5 and sigma value of 0.5

$$C_s = \frac{\Delta I}{I} \qquad (10)$$

where, ΔI is the difference value between the object and the background (mean value), I is the mean background intensity.

To compare various pre-processing methods, a number of synthetic clouds were generated by means of infrared scene simulator[7,10]. The infrared scene simulator (IRSS) uses the modified Gardener's Fourier series method, self-similar method, and Perlin's noise method to generate the synthetic infra-red clouds. The IRSS typically does the object creation and its modelling, background scene creation and it's modeling, and the integration of created IR object into simulated background scene and image rendering process. The snapshot of the IRSS with generated cloud is shown in Fig. 2.

The real infra-red video data containing the long-range small/point air targets is not available for study and analysis. Therefore the small/point targets were synthetically embedded in these clouds through a target embedding routine in MATLAB[11] environment with known target and background profile, as shown in Fig. 3.

Finally, these images were subjected to various filtering processes. Appropriate pre-processing filters were selected for simulation process. The parameters for comparative study (SCNR, differential intensity and input-output contrast values) were automatically generated and logged in a file for analysis. The run time snapshot of the pre-processing simulation program is shown in Fig. 4.

A total number of 50 types of background cloud sequences (each sequence with 25 image frames) were generated and targets with known target characteristics (target position, shape and gray-level difference between the target and the neighbouring background) were embedded in each of the image frame.

4. SIMULATION RESULTS AND THEORETICAL DISCUSSION

The clouds generated as above, were embedded with a point target with input SCNRs of 5 dB, 10 dB and 20dB (wrt the surrounding window of 5x5 pixels. The pre-processing filters discussed[1] were simulated on infra-red image frames as above. SCNR of the input and output images was calculated and the improvement in SCNR was found. The SCNR of the filtered output image was calculated in the same window of 5x5 pixels. The average performance of these filters over the full sample of clouds is presented in Fig. 5.

As seen in Fig. 5, no clear cut pattern is emerging with respect to the performance of any of the filters. Hence,

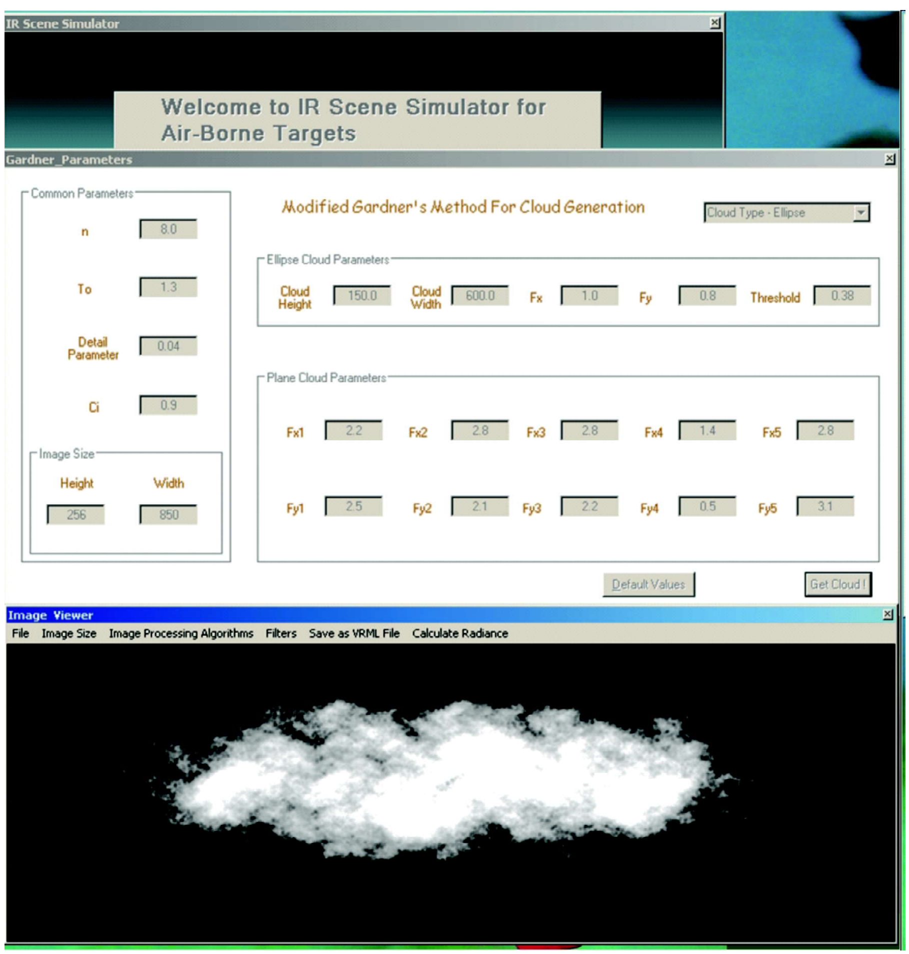

Figure 2. Infra-red scene simulator (IRSS) and a synthetically generated cloud.

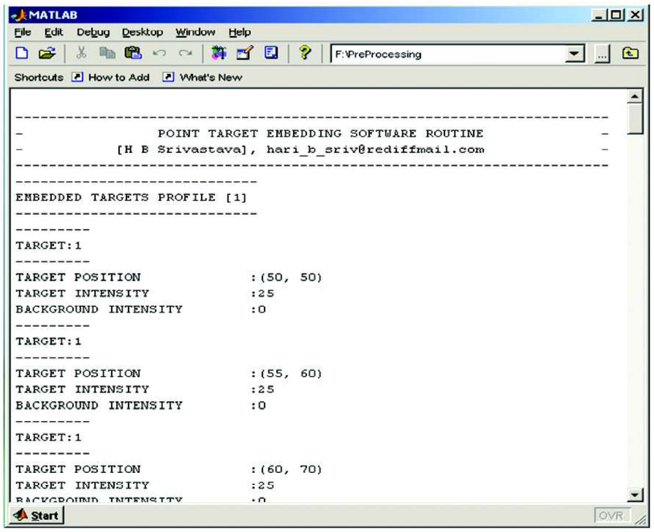

Figure 3. Infra-red scene simulator snap shot.

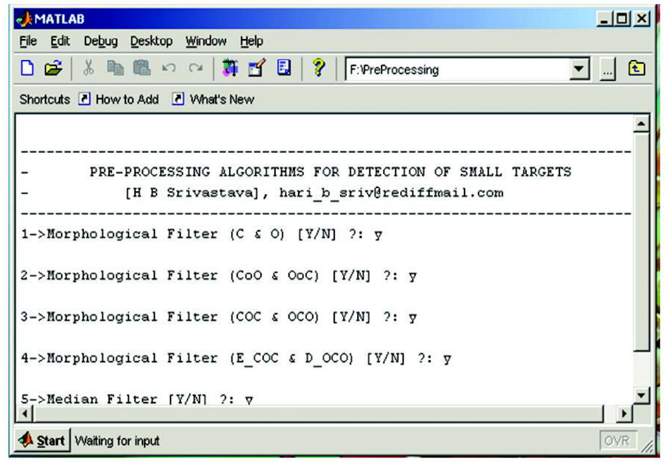

Figure 4. Run time snapshot of pre-processing simulation program.

there is a need to find an alternate parameter for comparison of algorithms. Contrast sensitivity, as defined above, was chosen as a parameter for comparing various filters, specifically, the ratio between the output contrast sensitivity and input contrast sensitivity was plotted.

The same target-background scenarios that were used for SCNR calculations were used for calculating contrast sensitivity. Encouraging results were seen. The five test cases were analysed on each of 50 image sequences with gray-level difference (GLD) of 2, 5, 10, and 20 between the target and the background on 8-bit gray-scale images. The results are similar for other test cases also. It is seen that max-min filter is almost always outscoring all other filters in terms of contrast sensitivity. It was also observed that there is a constant improvement in output contrast by various filters. Whenever, the input contrast is high, the output contrast saturates at 8-bit (255) value.

The max-min filter is defined as given in the following equation:

$$y(m,n) = \max[z_1, z_2, z_3, z_4] \tag{11}$$

where $y(m, n)$ is the output of the $(2N+1)^{\text{th}}$ order max-min filter and z_1, z_2, z_3 and z_4 are minimum values of the middle row vector, middle column vector and the two diagonal vectors of the convolution kernel centered around the pixel of interest, respectively. The larger the value of N, the more was the spike suppression. This property was used to detect small targets. The maximum operation was chosen with criteria to preserve edges and discontinuities

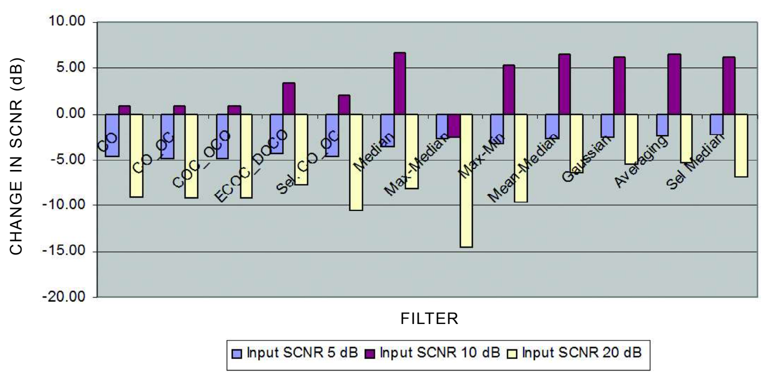

Figure 5. Filter performance on SCNR basis.

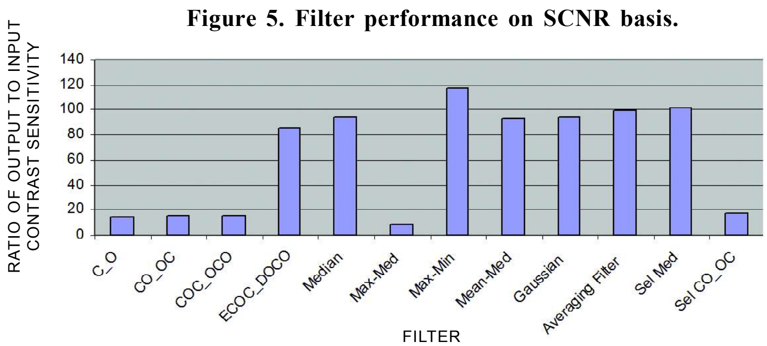

Figure 6. Filter performance for input GLD 2.

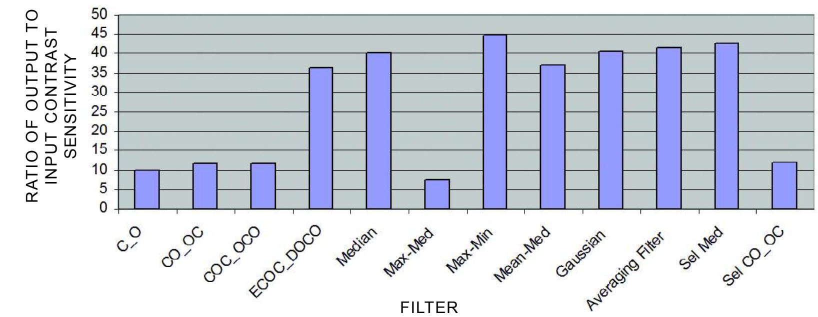

Figure 7. Filter performance for input GLD 5.

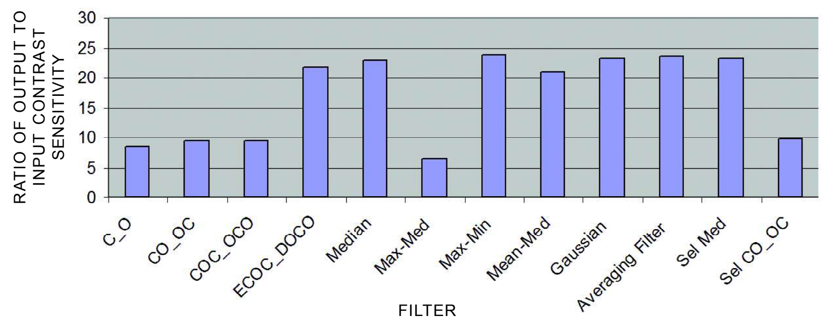

Figure 8. Filter performance for input GLD 10.

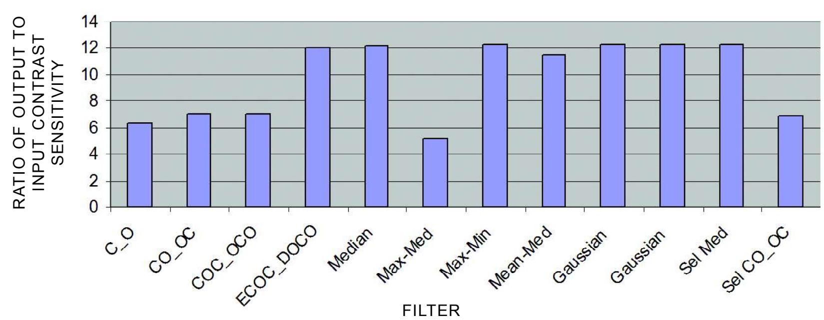

Figure 9. Filter performance for input GLD 20.

in the filtered signals. If other ranks are chosen rather than the maximum, it can be easily shown that the filter will tend to blur edges of the original signal. In many applications, all the z_i, s estimates may not be needed. The minimum operations on middle row vector, middle column vector, and the two diagonal vectors initially predict the background as the minimum intensity value over the horizontal, vertical or diagonal direction. This operation preserves the low-intensity targets, and hence helps to enhance the SCNR in the absolute difference image.

The graphs showing the performance of the simulated filters for GLD of 2, 5, 10, and 20 are shown in Figs 6, 7, 8, and 9, respectively.

5. CONCLUSIONS

Pre-processing filters are very useful to suppress the background and enhance the contrast sensitivity of the difference image frame for detection of small targets. From the simulation, it is seen that the statistical filters have superior performance in the present application. It was also found that max-min filter outperforms the other statistical filters. Moreover, the computational requirements are also O(n), making it an attractive choice for real-time application. Selective-median, improved hybrid morphological filter, median filter and max-median filter also perform satisfactorily if the input contrast of the target is good. However, their performance degrades for very low contrast targets.

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