

Infrared dim target detection based on fractal dimension and third-order characterization

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We propose an improved algorithm based on fractal dimension and third-order characterization to detect dim target with cluttered background in an infrared (IR) image. We also illustrate the performance and efficiency comparisons between the presented algorithm and the traditional fractal detection method on real IR images. The experimental results show that the proposed algorithm is robust and efficient for IR dim target detection.

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An important problem in infrared (IR) surveillance systems today is the detection of dim target under clutters. In such problems, the contrast between the target and the background is usually very low and the target is supposed to be embedded in quite strong noise. Besides, the size of target is too small and its texture is not obvious^[1]. As a result, the research of such problems becomes a challenging and meaningful task. Currently, the fractal theory has been widely used in the field of man-made target detection^[2-4]. However, the fractal methods are not only time-consuming, but also inaccurate. That is to say, the traditional fractal methods cannot meet the need of real-time target detection and have a low detection probability.

In this letter, we present an improved fractal algorithm based on the third-order characterization for IR dim target detection problems in a single image. The basic idea of the algorithm is to apply a coarse location based on the third-order characterization to position the target roughly at first, and then use a fine location based on fractal theory to get the exact detection result. The experimental results indicate that the proposed algorithm can not only raise the detection efficiency, but also improve the robustness.

Fractal theory provides a concise language for describing the complexity of both natural and social phenomena. As the basis of fractal analysis, self-similarity is defined as the property of a curve or a surface where each part of it is indistinguishable from the whole, or where the form of the surface is invariant with respect to scale^[5,6].

Fractal dimension is a quantificational parameter of fractal to characterize the roughness and self-similarity in an image. Fractal dimension is highly correlated with the human perception of image texture: the rougher the texture appears, and the larger the fractal dimension is. It has been indicated that the fractal dimension between man-made objects and the natural background is different. Thus, fractal theory is a powerful tool that can

be efficiently used for IR dim target detection.

Penland pointed out that the gray-scale images mapped from most nature objects accord to the fractal Brown stochastic field^[7]. Let $B_H(t)$ be a fractal Brown motion function, and its distribution is

$$P_r \left\{ \frac{B_H(t + \Delta t) - B_H(t)}{\|\Delta t\|^H} < y \right\} = F(y), \quad (1)$$

where $F(y)$ is a Gaussian distribution of a random variable y , t is an arbitrary point in the N -dimensional Euclidean space, and H is a parameter between 0 and 1 to illustrate the self-similarity or irregularity of the surfaces. The fractal dimension (FD) is related to both the parameter H and the topological dimension N :

$$\text{FD} = N + 1 - H. \quad (2)$$

If $F(y)$ is assumed to be $N(0, \sigma^2)$, it can be deduced from Eq. (1) that

$$E(|B_H(t + \Delta t) - B_H(t)|^2) = C |\Delta t|^{2H}, \quad (3)$$

where C is a constant. By taking the logarithmic form of Eq. (3), the H value can be determined by fitting the data set $\{\log E(|B_H(t + \Delta t) - B_H(t)|^2), \log |\Delta t|\}$ (using least square method). Half of the slope of the fitted line represents the parameter H .

By calculating the fractal dimension value of each pixel in the original image, we can get a new fractal dimension image. Then a threshold operation will be applied to the fractal dimension image to detect the real target.

However, calculating the fractal dimension image of an original image is time-consuming and also easily influenced by clutters. Therefore, an improved fractal algorithm based on the third-order characterization is presented to decrease the computation and raise the robustness.

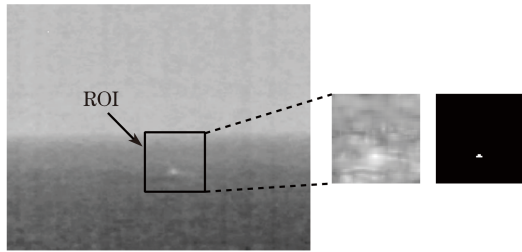


Fig. 1. IR dim target detection by the presented method.

In recent years, higher-order statistics (HOS) are widely applied to signal processing, in scenarios that always involve signal separation or characterization of non-Gaussian signals in a Gaussian background, which is usually the result of summing different noise processes. In IR dim target detection problems, the dim target is always thought as transient non-Gaussian signal, while the background is considered as stationary Gaussian signal. Thus, we get a good idea of using HOS to locate the target coarsely at first.

According to the statistical theory, for Gaussian noise, all cumulants of order greater than two are identically zero^[8–10]. Here, skewness, the normalized version of the third-order cumulant, is selected to measure the ‘Gaussianity’. Skewness is a quantity, related to the third moment, that tell us how symmetrical a distribution is^[11]. The skewness S of the image X is estimated by

$$S = \frac{\langle [X - \eta]^3 \rangle}{\sigma^3} = \frac{1}{N} \sum_{i=1}^N \left[\frac{x_i - \eta}{\sigma} \right]^3, \quad (4)$$

where η is the mean, σ is the standard deviation, $\langle \cdot \rangle$ is the mean operator, and S is a dimensionless quantity, characterizing the degree of asymmetry of a distribution around mean.

In order to locate the dim IR target coarsely, we can let a window with size of $M \times N$ slide on the original image from left to right and up to down, and then compute the skewness of each window. At last, the window that contains the dim target must have the maximum skewness value. According to this rule, our method can be described as a “finding non-Gaussian maximization window” process.

After coarse location, the target can be located finely by fractal theory. Because the coarse location eliminates a large area of background clutter and gets a region of interest (ROI) which only contains the target and a small part of the background, the improved algorithm can greatly increase the efficiency and robustness.

In Fig. 1, the left image is the original IR image with sea background. Its size is 282×227 pixels. The target is a man-made boat and has less than 12 pixels. By HOS, the target is located coarsely at first and a ROI containing the dim target is obtained (labeled in the rectangle). The middle image of Fig. 1 is the fractal dimension image of the ROI, and the right image is the detection result by adaptive threshold operation.

Now, we can get the whole procedures of the proposed method. Firstly, a coarse location using the third-order characterization is adopted to segment a ROI containing the dim target, and then the fractal dimension image of

the ROI is constructed. At last, a threshold operation is used for the fractal dimension image to get the detection result.

According to the above-mentioned “finding non-Gaussian maximization window” rule, we let a window with size of $M \times N$ slide on the original image and compute the skewness of each window. The values of M and N should not be too small or large. If they are too small, the continuity of the image gray scales may be destroyed and the noise will be regarded as the target by mistake; if they are too large, the details of the image may be lost and at the same time the computation will increase. After a great deal of experiments, M and N are selected in the range of 7–11.

Once getting the “maximum skewness value window”, we take the center of the window as the center and extend the window outward by 15 pixels (not beyond the boundary of the image) to get the ROI. This step is to guarantee the integrality of target. Then a fine location of the target based on fractal theory is applied to this region. When we compute the fractal dimension image of this region, the size of the sliding window should be considered carefully. If the size is too small, the number of pixels used for linear fitting is small, which will produce a big error; if the size is too large, the detection process will be disturbed by the background clutter.

Based on the improved algorithm discussed above, we carry out many experiments by MATLAB6.5 on a personal computer (P4 2.80 GHz, 512 MB). Here, we select two IR images, each of which has only one target, to show the advantages of our method. We compare the detection performance and efficiency between the presented algorithm and the traditional fractal method. The contrast of a target is defined by the difference in the brightness of the target and the background:

$$C = |f_t - f_b| / |f_t + f_b|, \quad (5)$$

where f_t is the average intensity value of the target and f_b is the average intensity value of the background.

Figure 2 shows the detection results of Fig. 1. The size of the image is 282×227 pixels. The target is a man-made boat and has less than 12 pixels. The contrast of the target is 0.1055. Figure 2(a) is the detection result of the presented method, and Fig. 2(b) is the detection result of the traditional fractal method. Obviously, the detection result in Fig 2(a) is better than that in Fig. 2(b), for the latter has a false target indicated at the bottom.

Figure 3(a) is an IR image with sky background. Its size is 289×212 pixels. The ROI containing the dim target (labeled in the rectangle) is obtained by HOS. The dim target is a flying object and has about 6 pixels. Its contrast is 0.2973. The detection result of the presented method is satisfying (Fig. 3(b)), while the result of the traditional fractal method has a false target at the bottom (Fig. 3(c)).

A series of experimental results have demonstrated that the improved algorithm has better detection performance than the traditional fractal method. Now, we give the quantitative evaluation by the false alarm probability P_f (under the condition of the detection probability $P_d = 0.9$). We test 80 IR images of different contrasts using the improved fractal method and the traditional

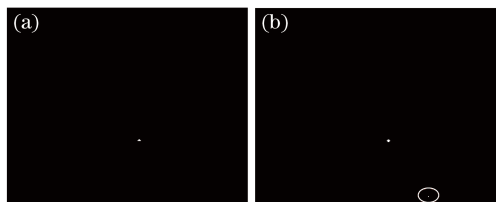


Fig. 2. Detection results for an IR image with (a) the presented method and (b) the traditional fractal method (the false target is indicated in the circle).

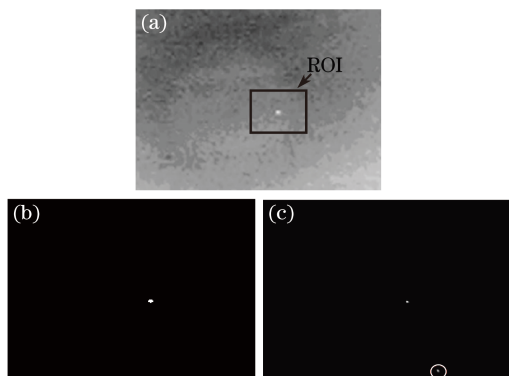


Fig. 3. Infrared image with sky background and detection results. (a) Original image; (b) detection result by the presented method; (c) detection result by the traditional fractal method (the false target is indicated in the circle).

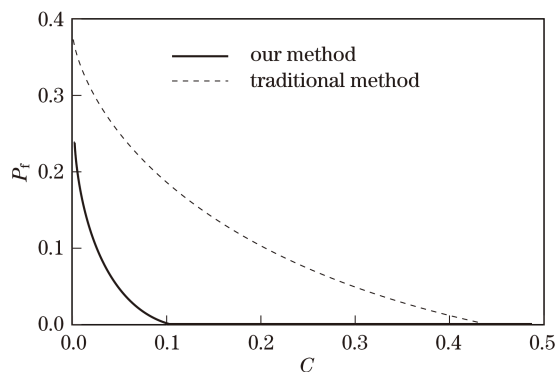


Fig. 4. False alarm probability P_f versus contrasts C for our algorithm and the traditional fractal algorithm.

fractal method. Fig. 4 shows the comparison of false alarm probability between the presented method and the

traditional fractal method. It is clear that our algorithm has a much better performance than the traditional fractal method.

We also compare the detection efficiency between the presented method and the traditional fractal method. The average computing time of our method for a single image is 0.4230 s, while the average computing time of the traditional fractal method is 6.5160 s. Obviously, although the presented method utilizes a coarse location before detecting the target finely, the computational complexity of the whole algorithm is still very low and it effectively overcomes the defect of huge computation cost of the traditional fractal method.

In conclusion, we present an improved detection method for IR dim target under complex background in a single image. Different from the traditional fractal method, the presented method detects the dim target in two steps: coarse location and fine location. In the presented algorithm, the coarse location of the target is obtained by the third-order characterization, and the fine location is based on the fractal method. The experimental results show that this improved algorithm overcomes the disadvantages of the traditional fractal methods and can detect the IR dim target robustly and quickly.

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