Adaptive detection for infrared small target under sea-sky complex background

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An adaptive Butterworth highpass filter is presented to detect a small target under a sea-sky complex background. By calculating the weighted information entropy of different infrared images, the cutoff frequency of the filter can be changed adaptively. Experimental results show that it is a robust small target detection method.

Introduction: In actual sea-sky conflicts, the background of a target is usually complex. For example, by reason of the sun's refraction, the waves of the sea can produce many high grey-level regions in infrared images, so-called 'sea clutter'. It has been regarded as a difficult task in most cases to detect or trace a small target under the conditions mentioned above. Denney and de Figuiredo presented a small target detection method based on the predication under the adaptive auto-regressive background [1]. Tom *et al.* put forward the morphologic operators for small target detection according to the prior knowledge of targets [2]. Peng and Zhou designed a 5 × 5 highpass template filter for real-time target detection [3]. Ye *et al.* provided a small target detection method based on wavelet transform modulus maxima [4]. Based on the analysis of various target detection methods, Hilliard pointed out that a lowpass IIR filter has a better comprehensive performance for clutter prediction [5]. In this Letter, we first analyse the frequency distribution of infrared small target images, and then present a new small target detection method based on the adaptive Butterworth highpass filter (BHPF) (Fig. 1). Experiments have proved that our method is robust.

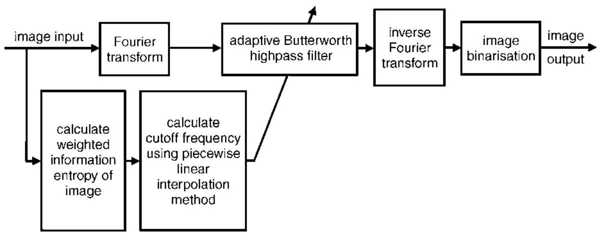

Fig. 1 *Block diagram of small target detective process*

Foundation of theory: To separate a small target from the background of the images, we analysed the characteristics of the images with an infrared small target through their frequencies. For the mild sky background, the images mainly consisted of low frequency components. For the complex sea clutter background, the images consist of middle frequency components mostly. For the small target under the backgrounds mentioned above, it consists of high frequency components of the images. Therefore the key problem is how to effectively separate middle frequency from high frequency. The BHPF is a simple filter in frequency domain, which possesses some particular features: not only maximum flat amplitude in the passband, but also smooth transition between low frequency and high frequency. The transfer function of the BHPF usually can be expressed as follows:

$$H(u,v) = \frac{1}{1+[\sqrt{2}-1][D_0/D(u,v)]^{2r}} \tag{1}$$

where r is the order of filter, which decides the slope of the curve diagram for the property of filtering. In our research case, the order is not the key factor which influents frequency separation, so we set $r=2$ to simplify our discussion. D_0 is the cutoff frequency which decides the position of frequency separation in the BHPF. Obviously, our problem now focuses on how to regulate the parameter value D_0 according to the different backgrounds of the images.

Adaptive regulation of cutoff frequency: Because the variance of a grey-level image only describes the deviation degree between pixels' grey and their mean in the meaning of statistics, it cannot provide any spatial information regarding the grey-value distribution of the images. Therefore, we propose an adaptive regulation strategy in terms of cutoff frequency based on the information entropy of different infrared images. The information entropy is an efficient approach to illustrate the complex degree of grey-value distribution upon an infrared image; it is defined as follows:

$$H = -\sum_{s=0}^{255} p_s \log\ p_s, \quad \text{when } p_s = 0, \text{ define } p_s \log\ p_s = 0 \tag{2}$$

where p_s is the probability of the grey-value s in the image ($\sum_{s=0}^{255} p_s = 1$). Although the information entropy of an image denotes the average information about the image, it neglects the importance of grey information. So it cannot represent our subjective judgements about the background of the image. Thus, we provide some modification to (2).

Generally speaking, in the infrared images with complex background, a small target and the clutter normally appear in the form of high grey-level. This largely impacts the direction of our subjective judgement for the image's information. To emphasis the contribution of high grey-value components to the information entropy of an image, we specify the grey-value s which corresponds to the probability p_s to the weight coefficient, and then modify (2) as follows

$$H' = -\sum_{s=0}^{255} s \cdot p_s \log\ p_s, \quad \text{when } p_s = 0, \text{ define } p_s \log\ p_s = 0 \tag{3}$$

H' can be named the weighted information entropy of the image. This formula provides an effective method to describe the information incorporated in different backgrounds because it combines the grey distribution information of infrared images with our subjective judgements. For example, in the case of a grey-level image which only includes $m(m \in N, 1 \le m \le 256)$ kinds of grey-value $s_1, s_2, \ldots, s_m$, if the probability of each kind value to appear is equal, the weighted information entropy of the image is expressed as:

$$\begin{aligned} H' &= -\left\{ s_1 \frac{1}{m} \log \frac{1}{m} + s_2 \frac{1}{m} \log \frac{1}{m} + \cdots + s_m \frac{1}{m} \log \frac{1}{m} \right\} \\ &= \left(\frac{s_1 + s_2 + \cdots + s_m}{m} \right) \cdot \log m \end{aligned} \tag{4}$$

The formula (4) denotes that the mean of grey-value is an effective way to describe the complex degree of an image when it has the same probability distribution. For example, it can be comprehended that the background of a small target can be estimated roughly by the mean brightness of the images when we observe some infrared images which have even grey change. So (4) is an effective formula which accords with our subjective judgement.

Based on the above analysis, we can now establish a corresponding connection of an image between the weighted information entropy and cutoff frequency of the BHPF. Our regulation strategy can be described by following two steps: first, storing the weighted information entropy and appropriate cutoff frequency from some typical small target images with different backgrounds according to the prior knowledge; secondly, calculating cutoff frequency of the BHPF using the piecewise linear interpolation method in a real-time system.

Image binarisation: If some low frequency components have been cut off, the general grey-level of the images which are received by inverse Fourier transform will be decreased. So we cannot binarise the images by a fixed threshold. To decrease possible candidate targets under the requirement that the real target cannot be discarded, we choose the binarisation threshold which is 0.95 times of maximal grey-value in filtered images. Experiments show that this is an effective method.

Experimental work: Fig. 2 shows the filtered effect of several images under different clutter backgrounds in adaptive BHPF. To compare our method with others, two common metrics are used to evaluate the performance of the filters [5]. They are defined as follows:

$$\text{signal-to-clutter ratio gain: } SCR\ Gain = \frac{(S/C)_{out}}{(S/C)_{int}} \tag{5}$$

$$\text{background suppression factor: } BSF = \frac{C_{in}}{C_{out}} \tag{6}$$

where S is the signal amplitude and C is the clutter standard deviation within a single frame. The experimental data are listed in Table 1, which shows that the filtering performances of several common filters are very close with each other when they are used for the mild background of infrared images [see row A1 in Table 1]. However, once the images are influenced by clutter, the filtered effect of median and wavelet modulus are better than 5×5 highpass template. Because a wavelet modulus filter essentially is an edge detection method, its filtering performance will be worse when the grey of the background changes dramatically [see row E1 in Table 1]. It is obvious that adaptive BHPF maintains better performance for small target detection under the different backgrounds, therefore the BHPF is a robust method for small target detection.

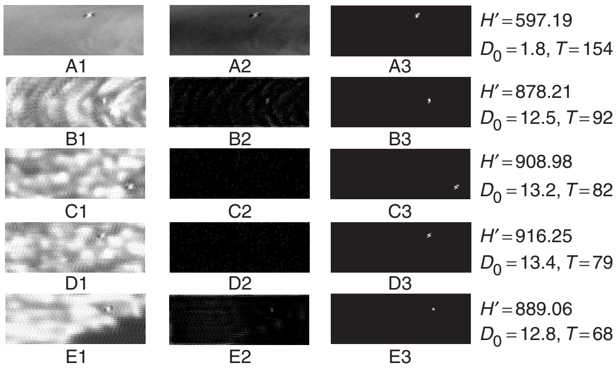

Fig. 2 *Small target detective samples based on adaptive BHPF*

A1, B1, C1, D1, E1: original infrared images under different clutter background
A2, B2, C2, D2, E2: filtered results of adaptive BHPF
A3, B3, C3, D3, E3: binarisation results
H': weighted information entropy of original image
D_0: cutoff frequency of adaptive BHPF
T: threshold of binarisation

Table 1: Comparison of several small target detective method

Filtering method	Median		5×5 highpass template		Wavelet modulus		Adaptive BHPF	
Metrics	SCR gain	BSF	SCR gain	BSF	SCR gain	BSF	SCR gain	BSF
A1	1.0893	1.3987	0.5553	0.5328	1.7181	1.2989	1.4201	1.4200
B1	2.5452	2.3341	1.6969	1.2474	3.2544	1.6293	3.9286	3.9790
C1	3.7408	2.6378	2.0721	1.3618	4.3981	2.2177	5.5290	5.1149
D1	2.3960	2.5689	1.7351	1.4055	2.8359	1.3751	4.4761	4.6403
E1	12.3391	4.4281	8.1789	2.3905	False	False	17.6188	6.4329

A1, B1, C1, D1, E1: original infrared images shown in Fig. 2

Conclusions: An adaptive BHPF based on the weighted information entropy of the images is proposed to detect a small target in infrared images. Our experimental results prove that our method has robust performance to restrain different clutter. In a real-time system, a small tracing window will be established in terms of the correlative relationship for positions between two adjacent serial frames, which will dramatically decrease the complexity of algorithm.

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