Sea-Sky-Line/Coastline Extraction in Infrared Imagery Based on Structure Tensor and Hough Transform

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***Abstract*—Sea-sky-line/coastline extraction is a key problem in infrared maritime target search and track systems. However, the current studies of sea-sky-line/coastline detection in infrared imagery usually aim for detection accuracy or time saving unilaterally, and it is seldom suitable for practical applications in complex scenarios. To cope with this problem, a novel sea-sky-line/coastline extraction method based on the structure tensor and Hough transform is proposed in this paper. Firstly, the Gaussian filter based pre-processing is applied on the infrared image to eliminate the clutters. Then, the Gaussian structure tensor is proposed to enhance the line property of sea-sky-line/coastline and a segmentation threshold is selected to binarize the image. Finally, on the basis of line property of sea-sky boundary in binary image, the Hough transform is applied to effectively locate the sea-sky-line/coastline. Extensive experiments show that the proposed sea-sky-line/coastline extraction method not only has an outstanding detection accuracy under different scenarios but also has the potential of real-time hardware processing.**

***Index Terms*—sea-sky-line/coastline extraction, infrared imagery, structure tensor, Hough transform**

I. Introduction

The extraction of sea-sky-line or coastline (SSLoCL) is a key technique in maritime infrared search and track (IRST) systems, where both accuracy and arithmetic speed are indispensable [1]-[3]. However, currently the research and application of SSLoCL extraction are mostly unilateral pursuit of detection accuracy or time saving, which is rarely suitable for practical applications in complex scenarios. Therefore, the SSLoCL extraction is a difficult and challenging problem. Although a number of SSLoCL detection methods have been proposed in the past ten years [4]-[6], it is still an open issue.

In infrared images, the SSLoCL presents itself as a dividing line of a pixel set of maximum gradient between sea region and sky region, which is approximately a straight line without consideration of peak clutters, sea surface warping and imaging distortion. Based on this assumption, many sea-sky line extraction algorithms are developed and have obtained certain effects. In [7], [8], the gradient magnitude map of original image is calculated and the Radon transform (RT) is performed on gradient image to select sea-sky line. In [9]-[11], the Canny edge detector is firstly utilized to generate binary edge map, and then Hough transform is applied to identify the horizon line. Kim and Lee [12] presented a coastline detection algorithm based on column directional gradient, and the inlier horizon pixels are identified using the RANSAC line fitting method. Above three conventional methods have outstanding performance in saving the time and computational complexity. However, these methods are quite sensitive to intricately distributed clutters and strong edges, which eventually leads to high false detection rate. Recently, Zou et al. [13] made advantage of the Shearlet transform which accounts for the geometrical properties of edges to extract directly the information about the orientation of the sea-sky line. Ma et al. [14], [15] proposed a linear fitting method based on least squares and line segment detection to extract sea-sky line. In [16], the sea-sky line region is located by using the textural gray-level co-occurrence matrix, and then a clustering method is adopted to form them by straight-line fitting. These linear fitting based methods can analyze the directional information and provide edge geometric features of sea-sky line. Nevertheless, these linear fitting methods suffer high computational complexity and are not suitable for real-time applications. Based on above discussions, the main shortages of those classical methods can be summarized as follows:

* The SSLoCL can be treated as a straight line approximately, but it is not a real one because of the sea surface warping and imaging distortion. Therefore, the traditional methods such as Hough, Radon and RANSAC transform cannot directly fit the SSLoC effectively.

* The SSLoCL is a thick and rough edge in the infrared image, while the traditional gradient-based edge detection method can only detect thin edges, and cannot fit a complete sea-sky line well, such as Canny detector.

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* The Shearlet-based or linear fitting based SSLoCL extraction algorithms have much better detection performance than above methods, but it is consuming too much time.

To overcome the disturbance of above three factors, the Gaussian structure tensor is presented in this paper to eliminate clutters and depict the thick and rough edge property of SSLoCL efficiently, and then the SSLoCL is accurately extracted by Hough transform, which is well-known for line segment detection. As far as we known, this is the first time that structure tensor is introduced in the field of infrared sea-sky-line/coastline detection. By the utilization of structure tensor and Hough transform, a novel SSLoCL extraction scheme is proposed with both outstanding detection accuracy and low time-consumption in this paper.

The remainder of this paper is organized as follows: In Section II, we describe the proposed SSLoCL extraction algorithm in detail. The experimental results are shown in Section III, and the conclusions are followed in Section IV.

II. Sea-Sky-Line/Coastline Extraction Method

A. Gaussian Filter for Pre-processing

As the captured infrared images have been degraded by clutter noises during sensor imaging and transmission, the pre-processing is required before SSLoCL detection. Gaussian filter is one of the most widely used pre-processing smooth filtering methods, and it can be effectively employed to suppress clutter noises and protrude the line intensity and width properties of SSLoCL. The original image $g(x, y)$ is filtered by Gaussian kernel function $G(x, y)$, and the filtered image $f(x, y)$ can be written as follow:

$$f(x, y) = g(x, y) * G(x, y) \tag{1}$$

here (*x*, *y*) denotes the pixel location, and the Gaussian kernel function $G(x, y)$ is expressed as:

$$G(x, y) = \exp(\frac{x^2 + y^2}{2\sigma^2}) \tag{2}$$

where σ is the standard deviation of the Gaussian kernel function and is empirically set to 2.

B. Structure Tensor for Edge Property of SSLoCL

Due to sea surface warping and imaging distortion, the SSLoCL is not a real straight line. It appears as a thick, rough and approximately straight-line edge in infrared image. Therefore, the traditional gradient-based edge detection method such as Canny detector, can only detect thin edges, and cannot fit a complete sea-sky line well. Motivated by the successful applications of local structure tensor in strong edges detection [17], [18], the Gaussian structure tensor (GST) is presented to efficiently identify sea-sky line in this paper. Given the Gaussian filtered infrared image $f(x, y)$, the partial derivatives in the x and y directions at location (*x*, *y*) can be calculated by:

$$D_x[f(x, y)] = \frac{f(x+1, y) - f(x-1, y)}{2} \tag{3}$$

$$D_y[f(x, y)] = \frac{f(x, y+1) - f(x, y-1)}{2} \tag{4}$$

where $D_x[f(x, y)]$ and $D_y[f(x, y)]$ are the partial derivative value in x direction and y direction, respectively. And the GST is introduced as:

$$GST(x, y) = \begin{Bmatrix} D_x^2[f(x, y)] & D_x[f(x, y)]D_y[f(x, y)] \\ D_x[f(x, y)]D_y[f(x, y)] & D_y^2[f(x, y)] \end{Bmatrix} \tag{5}$$

Their corresponding maximum eigenvalue $\lambda_{\max}(x, y)$ and minimum eigenvalue $\lambda_{\min}(x, y)$ of GST map can be computed as follows:

$$\begin{cases} \lambda_{\max}(x, y) = \frac{1}{2}\left\{ D_x^2[f(x, y)] + D_y^2[f(x, y)] + \sqrt{\left\{D_x^2[f(x, y)] - D_y^2[f(x, y)]\right\}^2 + 4D_x[f(x, y)]D_y[f(x, y)]} \right\} \\ \lambda_{\min}(x, y) = \frac{1}{2}\left\{ D_x^2[f(x, y)] + D_y^2[f(x, y)] - \sqrt{\left\{D_x^2[f(x, y)] - D_y^2[f(x, y)]\right\}^2 + 4D_x[f(x, y)]D_y[f(x, y)]} \right\} \end{cases} \tag{6}$$

Therefore, the eigenvalues difference measure (GTEDM) of GST map can be defined as:

$$GTEDM(x, y) = \exp[\lambda_{\max}(x, y) - \lambda_{\min}(x, y)] \tag{7}$$

Since these two eigenvalues $\lambda_{\max}(x, y)$ and $\lambda_{\min}(x, y)$ can be used as feature descriptors of edge geometric information, two distinct cases are considered: (1) If $\lambda_{\max}(x, y) \approx \lambda_{\min}(x, y)$, then $GTEDM(x, y) \approx 0$, hence the pixel location (*x*, *y*) is considered as flat region (residual noise component and background clutters) pixel. (2) If $\lambda_{\max}(x, y) \gg \lambda_{\min}(x, y)$, then $GTEDM(x, y) \gg 0$, this means that a strong edge pixel of the filtered image is appeared at pixel location (*x*, *y*). Based on above two distinct cases and the above-mentioned properties of sea-sky-line/coastline, the GTEDM can be efficiently used to further suppress background clutters and depict the thick and rough edge property of SSLoCL.

C. Binarization for Candidate Pixel Sets of SSLoCL

After the calculation of GTEDM map, the GTEDM image is separated by selecting a threshold value, and then the candidate pixel sets of sea-sky-line/coastline are left in binary image. The binary operation is derived as:

$$Binary[GTEDM(x, y)] = \begin{cases} 0, & GTEDM(x, y) < Thr \\ 1, & GTEDM(x, y) \geq Thr \end{cases} \tag{8}$$

Based on the statistics and observation of sea-sky/sea-land line extraction processing of 89 scene images, the threshold value is empirically set $Thr = 0.005$ in our experiments. In Fig. 1, the whole computation procedure of candidate pixel sets of SSLoCL based on GTEDM is shown. Fig. 1(a) shows the original maritime infrared image, and its edge detection result of canny operator is shown in Fig. 1(b). Fig. 1(c) shows the computed GTEDM map of original infrared image, and the candidate pixel sets of coastline after binary operation on GTEDM map is shown in Fig. 1(d). It can be seen from

Fig. 1(b), due to the disturbance of clutter noises, sea surface warping and imaging distortion, the coastline appears a discontinuous line after Canny edge detection and a false coastline is appeared under the real one. Compared with the false detection of Canny edge operator in Fig. 1(b), the result of Fig. 1(d) can well present the true coastline and the false one is suppressed in the binary image of GTEDM map. This is because although the coastline might be degraded by peak clutters, sea surface warping and imaging distortion, the GTEDM map can still perceive thick and rough edges while suppressing thin edges.

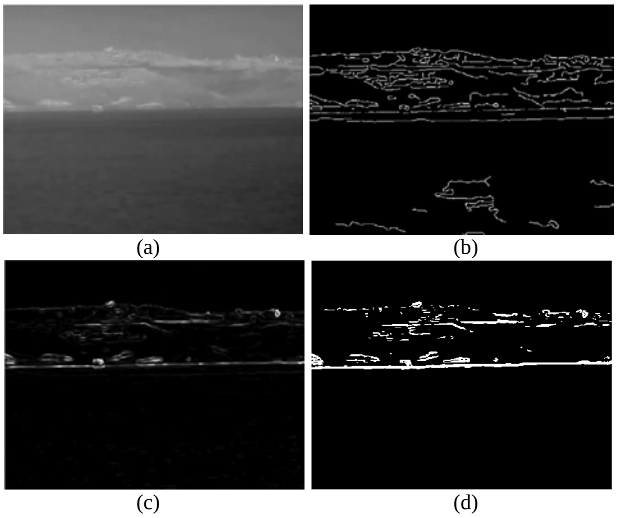


Figure 1. The illustration of whole computation procedure of candidate pixel sets of SSLoCL based on GTEDM. (a) Original maritime infrared image; (b) Canny edge detector on infrared image; (c) Computed GTEDM map; (d) Candidate pixel sets of coastline after binary operation on GTEDM map.

D. *Hough Transform for SSLoCL Extraction*

Compared with other line extraction methods, such as least squares, RANSAC and Radon transforms, the Hough transform has the advantages of easy implementation and better anti-interference. Hough transform converts line in image domain into $k-b$ parameter space through linear equations by making full use of the duality of points and lines, and then the detection of a given straight line in image domain is transformed into the peak value search of accumulator in parameter space. Given a line in the image domain, its equation can be written as:

$$y = kx + b \tag{9}$$

However, when the straight line is vertical or close to vertical, the slope of the line is infinite or close to infinity, so it cannot be expressed in *x-y* parameter space. In order to solve this problem, the normal line in $\rho-\theta$ polar coordinates can be used to depict the line in *x-y* parameter space, that is:

$$x\cos\theta + y\sin\theta = \rho \tag{10}$$

The illustration of Hough transform for SSLoCL extraction is shown in Fig. 2. The parameters of a straight line in *x-y* coordinate system are shown in Fig. 2(a), and the Sine parametric curves of a line in $\rho-\theta$ coordinate system are shown in Fig. 2(b). In Fig. 2(c), the work mechanism of two-dimensional accumulator units in $\rho-\theta$ coordinate system is presented. As shown in Fig. 2(b), the intersection point (ρ^*,θ^*) corresponds to a straight line both through (x_1, y_1) and (x_2, y_2). And it can be seen from Fig. 2(c), when two Sine parametric curves intersect at point ($\rho^* \in [\rho_{\min}, \rho_{\max}]$, $\theta^* \in [\theta_{\min}, \theta_{\max}]$), the corresponding accumulator unit is added by 1. Hence, by this analogy, the point (that is peak value point of the accumulators) with the greatest number of intersections (ρ^*,θ^*) of Sine curves represents the polar coordinate parameters of the longest straight line. By using Hough transform on the candidate pixel sets, the position of the optimal straight line is located. Because we have obtained the maximum value point (ρ^*,θ^*) of the accumulators, the straight line can be computed by:

$$y = kx + b = \frac{\rho^* - x\cos\theta^*}{\sin\theta^*} = -\left(\frac{\cos\theta^*}{\sin\theta^*}\right)x + \frac{\rho^*}{\sin\theta^*} \tag{11}$$

According to the calculation of above four steps, the coastline parameters of Fig. 1(d) are finally obtained by the decision of the two-dimensional accumulators, and the coastline parameters are marked by yellow font, as shown in Fig. 2(d). Accordingly, the result of coastline extraction of Fig. 1(d) is obtained by bringing the selected optimal coastline parameters $(\rho^*,\theta^*) = (-169,-85)$ into Equation (11). The final results of coastline extraction of Fig. 1(a) are shown in Fig. 3.

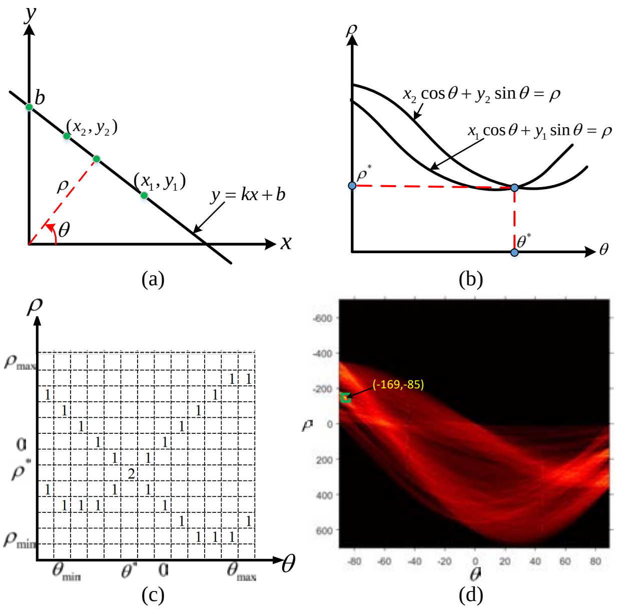
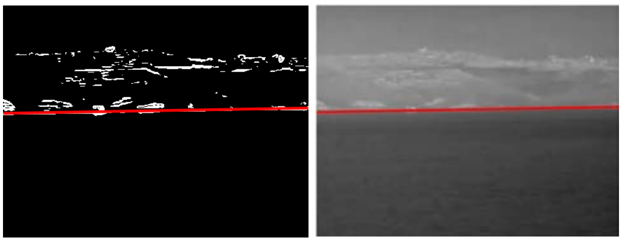


Figure 2. The illustration of Hough transform for SSLoCL extraction. (a) Parameters of a straight line in *x-y* coordinate system; (b) Sine parametric curves of a straight line in $\rho-\theta$ coordinate system; (c) The work mechanism of two-dimensional accumulator units in $\rho-\theta$ coordinate system; (d) The coastline parameters of Fig. 1(d) are obtained by decision of the two-dimensional accumulators.



(a) (b)

Figure 3. The final results of SSLoCL extraction of Fig. 1(a). (a) The result of straight-line detection of Fig. 1(d); The final result of coastline extraction in Fig. 1(a).

III. Experiments

In this section, several experiments were induced to validate the effectiveness of the proposed SSLoCL extraction method. Firstly, the infrared maritime test dataset for experiments is introduced. Then, the effects of different parameter configurations in the proposed method is discussed. Finally, some baseline methods are conducted for performance comparison with proposed method. These methods are performed in Matlab 2016a on the computer with 3.2 Ghz Intel i5-6500 CPU and 8 Gb random access memory.

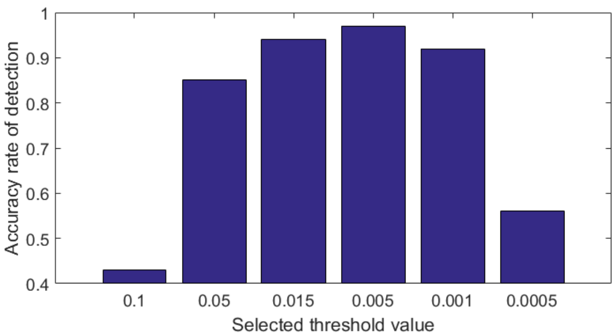


Figure 4. The detection accuracies of different threshold values in the step of binary operation.

A. Test Dataset

Four real infrared image sequences with sea-sky/sea-land background are used for conducting the experiments. These four sequences are labeled as sequences 1-4 and each sequence has 300 frames of size 640×480. Fig. 5(a1-4) show the representative frames of the four infrared sequences, respectively. Fig. 5(a1) is the 17th frame of infrared image sequence 1 and represents the infrared sequence with highly cluttered sea-land background. Fig. 5(a2) is the 132nd frame of sequence 2 and denotes the infrared sequence with high sea clutters. Fig. 5(a3) is the 105th frame of sequence 3 and depicts a sequence with a weak sea-sky line against the interference of strong tail waves of transverse moving vessels. Fig. 5(a4) is the 211st frame of sequence 4 with the sea-sky line corrupted by the ships, which is the near infrared sequence selected from Singapore Maritime Dataset [19]. Therefore, the test images are diversified in SSLoCL form and background clutter type. Testing on this dataset proves that the algorithm is suitable for different scenarios.

B. Effects of Parameters

In this part, the experiment is induced to discuss the effects of different parameter configurations on the performance of the proposed SSLoCL extraction method. In the proposed algorithm, the only parameter that needs to be discussed is the threshold value of the binary operation in step 3. In this experiment, 89 infrared scene images were processed by the proposed method with different threshold values. The detection accuracies of different threshold values are shown in Fig. 4, and it indicates the threshold value $Thr = 0.005$ can be suitable for different infrared maritime scene images.

C. Comparison to Baseline Methods

In this part, the comparisons with different baseline methods are performed to verify the efficiency of the proposed method. The RANSAC line fitting (RLF) [12], Canny aided Hough transform (CAHT) [11] and Shearlet transform (ST) [13] are chosen as the representative state-of-the-art SSLoCL detection methods. Fig. 5 shows the results of SSLoCL detection in four sequences with different methods. Fig. 5(a1-4) show the representative frames of the four infrared sequences, respectively; Fig. 5(b1-4) are the detection results of RLF method; Fig. 5(c1-4) are the detection results of CAHT; Fig. 5(d1-4) are the detection results of ST; Fig. 5(e1-4) are the detection results of the proposed method. It can be seen from Fig. 5, for these four real infrared maritime images, the proposed method can be more accurately detect the SSLoCL in the effect of different disturbing factors, and the detection accuracy performance is superior to that of the other representative SSLoCL extraction methods. Here, we give an evaluation criterion of detection accuracy: it is considered to be accurate if the detection result overlaps with the actual SSLoCL by more than 60%. In addition, the average time usage is considered in this experiment for the arithmetic speed requirements of practical applications. As shown in Table I, testing on these selected 1200 frames, both accuracy rate and arithmetic speed of the proposed method are greatly superior to other state-of-the-art methods. RLF-based method obtains highest false detection accuracy rate among these methods, and it takes a lot of time to process images because of random edge-point sampling and inline consistency verification. For CAHT based method, the cost of time is acceptable, but it still cannot achieve a considerable detection result due to Canny detector fails to accurately describe the thick and rough edge property of SSLoCL. The ST-based method is greatly better than RLF-based and CAHT-based methods in detection accuracy, but it is the most time consuming method on account of the multiplex and complex analyses of edge information in wavelet domain.

TABLE I. Detection Result Comparisons of Different Methods on the Selected 1200 Frames

Methods	*RLF*	*CAHT*	*ST*	*Proposed*
Accuracy rate	58.5%	65.4%	85.2%	96.7%
Time (ms)	1172.5	132.8	5133.9	118.4

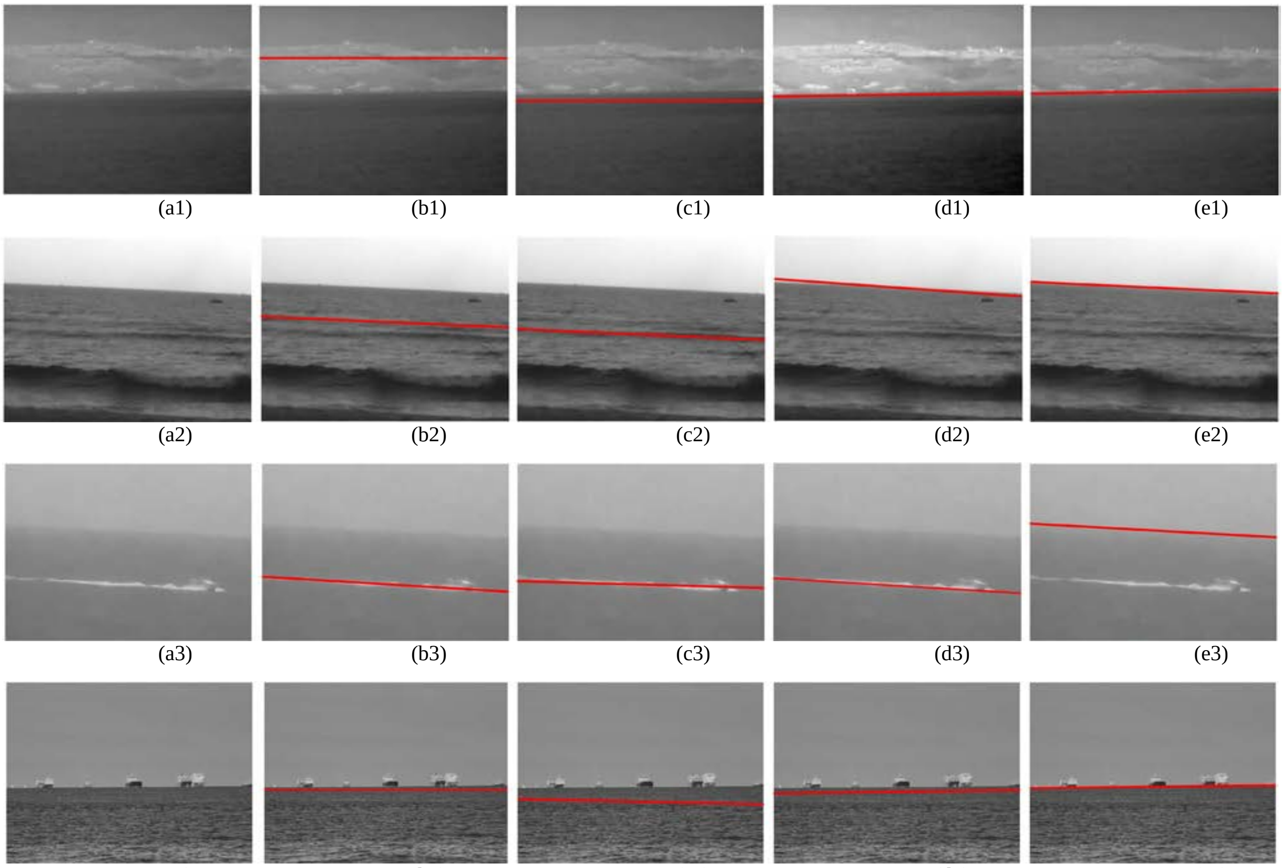


Figure 5. The comparison results of SSLoCL extraction with different methods. (a1-4) show the representative frames of the four infrared sequences, respectively; (b1-4) are the detection results of RLF method; (c1-4) are the detection results of CAHT; (d1-4) are the detection results of ST; (e1-4) are the detection results of the proposed method.

IV. Conclusions

To adequately exploit the thick and rough edge property of sea-sky-line/coastline, a simple but effective sea-sky-line/coastline extraction method based on the combination scheme of Gaussian structure tensor and Hough transform is proposed in this paper. The clutter noises are eliminated and the candidate point sets of sea-sky-line/coastline are perceived by the Gaussian structure tensor, so the proposed method is robust to peak clutters, sea surface warping and imaging distortion. The sea-sky-line/coastline is extracted and located by using Hough transform to efficiently estimate the straight-line parameters. Extensive experiments on real infrared maritime sequences validate that the proposed method have a better performance in both detection accuracy and time saving than compared state-of-the-art methods, including RANSAC line fitting, Canny aided Hough transform and Shearlet transform. Moreover, the proposed method can be used to detect sea-sky-line/coastline in visible optical images and achieve considerable detection results.

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