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Infrared ship target image smoothing based on adaptive mean shift

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***Abstract*—Infrared (IR) image denoising is important for IR image analysis. In this paper, we propose a method based on adaptive range bandwidth mean shift for IR ship target image smoothing, aiming to effectively suppress noise as well as preserve important target structures. First, local image properties, including the mean value and standard deviation, are combined to build a salient region map, and a thresholding method is applied to obtain a binary mask on the target region. Then, we develop an adaptive range bandwidth mean shift method for image denoising. By associating the range bandwidth of the mean shift with local region saliency, we can adjust the bandwidth adaptively, thus to smooth the background region while preserving important target structures. Experimental results show that this method works well for IR ship target images with different backgrounds. It demonstrates superior performance for image denoising and target preserving, compared with some existing image denoising methods.**

I. Introduction

Due to the advantage of being able to work at night time, and in adverse weather conditions such as fog and rain, infrared (IR) imaging systems have been widely used in many applications, such as target detection, object recognition, and security surveillance [1, 2]. However, IR images are usually characterized by low signal-to-noise ratio (SNR) and low contrast [3], especially for IR ship images with sea background. Heavy noise and sea clutters will reduce the quality of IR images and thus increase the difficulty of IR image analysis. Therefore, IR image denoising and enhancement has attracted increasing interests over the last few years [4]. It is important to reduce noise, suppress complex backgrounds and enhance the target. In addition, to make the filtered image more useful for different applications, such as feature extraction, target detection, and recognition, it is necessary to preserve important features, such as edges, corners and other target structures, during the denoising process [5]. Many edge preserving denoising methods have been developed [6], such as median filtering [7], anisotropic diffusion filter [8], bilateral filtering [9], Kuwahara filter [10], and mean shift filtering [11]. However, as different noises have different properties, it is difficult to design a algorithm for all situations [12]. The median filtering is one of the most popular smoothing methods; it performs well for reducing impulse noise while preserving edges, and it is simple and computationally efficient. However, as this method treats all pixels with fixed parameters, it may smooth some fine structures, and may cause streaking effects in the filtered image [15]. The anisotropic diffusion method is an effective denoising method which can iteratively smooth regions with small gradient while preserving regions with large gradient. Whereas the anisotropic diffusion method only considers the local gradient information of each pixel, it may smooth some important structures with low gradient, for example, blurred edges of a ship target in IR images. The bilateral filtering method combines both intensity and spatial distances to better preserve details, and it has been widely used for image denoising. However, for IR images with low contrast, the bilateral filtering will blur some important structures. In addition, this filter treats high frequency noisy pixels as edges, and hence it can not remove the high frequency noise in the smoothing process. The Kuwahara fitler is an edge-preserving filter which is commonly used for image and video abstraction. This filter can properly smooth details in high contrast regions and preserving boundaries in low contrast regions. Unfortunately, the Kuwahara filter may cause block artefacts and it is unstable for images with noises [16]. The mean shift smoothing algorithm is an effective discontinuity preserving denoising method, which identifies local modes of the underlying distribution in the joint spatial-range domain. In the process of mean shift filtering, the spatial bandwidth and the range bandwidth are important for the performance. Generally, a large bandwidth may cause over smoothing while a small one cannot provide effective smoothing. One solution to this problem is to make the bandwidth variable, thus to choose different bandwidth for different regions. In recent years, some new techniques, such as non-local means based filter [13] and guided filter [14], are also considered to be promising edge-preserving denoising methods. Although non-local means method shows powerful performance for denoising, how to optimally set the parameters of the method is still a question. For the guided filter, as it is ambiguous to determine which edge should be smoothed and which should be preserved, the guided filter shares a common limitation of other methods. That is it may cause halos near some edges when unsuitably smoothed [6].

In this paper, we propose an adaptive range bandwidth mean shift smoothing method for IR ship target images. First, to separate the ship target region from the background region, we propose a salient target region detection method based on local region properties. Then, we develop an adaptive range bandwidth selection method by associating the range bandwidth with local region saliency, thus to achieve the purpose of denoising while preserving important target structures.

The paper is structured as follows. In Section II, we introduce the detailed procedure of the proposed method. Section III demonstrates the experimental results on real images. Finally, conclusion is presented in Section IV.

II. Proposed Method

The flowchart of the proposed method is shown in Fig. 1. Details are given in the following sections.

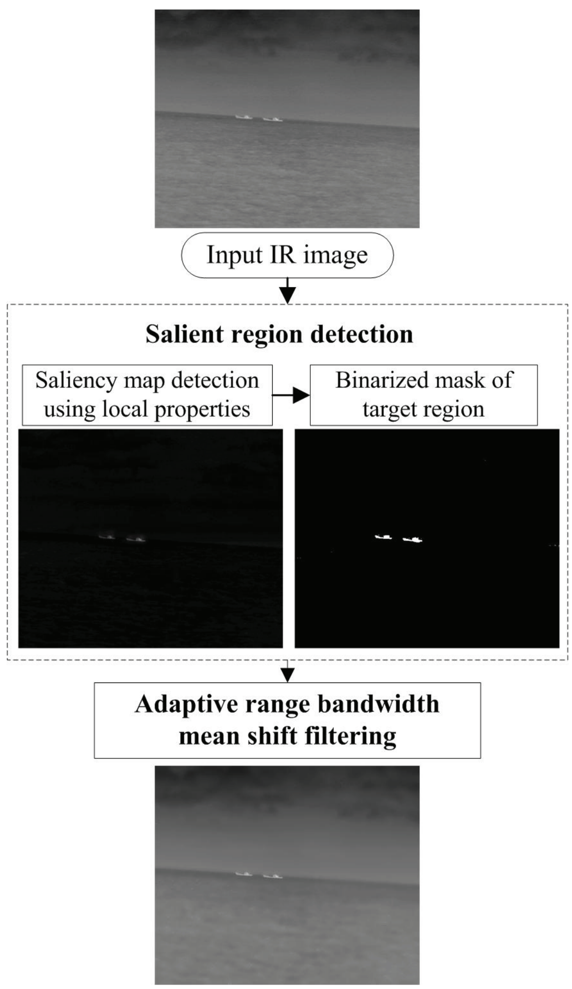


Fig. 1. Flowchart of the proposed method.

A. Salient target region detection

In this paper, we deal with IR ship target images with sea or sea-sky background, and Fig. 2 shows some samples. From Fig. 2 we can see that although the IR images have different backgrounds and ship targets, there are still something in common. Generally, the sky background is much simple; the ship target region is a connected region with high visual saliency and high local contrast comparing with its surrounding backgrounds; and the sea background is much complex with sea wave clutters. To effectively smooth the background while preserving the target, it is reasonable to distinguish the target from the background using their intensity characteristics. Therefore, before the denoising process, we propose a salient region detection method to highlight the ship target region. A simple and effective way of describing local region intensity characteristics is to use its mean and standard deviation values. Inspired by the work in [17],

Fig. 2. Samples of IR ship target images.

we use a block-based representation to calculate the local region saliency. Given an IR image I with size $W \times H$, we first divide the image into $M \times N$ non-overlapping blocks $\{B_{11}, ..., B_{1N}; ...; B_{i1}, ..., B_{iN}; ...; B_{M1}, ..., B_{MN}\}$. B_{ij} is an $s \times s$ image block. In the implementation, we set $s = 11$. Then local mean and standard deviation differences are used to highlight the ship target region. We calculate standard deviation differences of the adjacent blocks horizontally and vertically, respectively, and the larger value is taken as the standard deviation difference, denoted as sdf. Similarly, we calculate the mean difference of the adjacent blocks horizontally and vertically, and the smaller value is taken as the mean difference, denoted as mdf.

$$sdf(B_{ij}) = \max\left((S_{i,j} - S_{i,j+1}), (S_{i,j} - S_{i+1,j})\right) \quad (1)$$

$$mdf(B_{ij}) = \min\left((M_{i,j} - M_{i,j+1}), (M_{i,j} - M_{i+1,j})\right) \quad (2)$$

where $M_{i,j}$ and $S_{i,j}$ are the mean and standard deviation values of the block B_{ij}, respectively. The standard deviation difference map indicates the vertical difference while the mean difference map indicates the horizontal difference. We combine the two difference maps in the following way, thus to highlight regions with greater differences comparing to its neighborhood.

$$I_c(B_{ij}) = \sqrt{\left(mdf(B_{ij})\right)^2 + \left(sdf(B_{ij})\right)^2} \tag{3}$$

As the intensity distributions of the IR image vary according to each row, to enhance the ship target, a row mean subtraction method is applied on the original IR image I and the combined image I_c.

$$R_m(y) = \begin{cases} R_y - R_y^m, & \text{if } I(x,y) > R_y^m \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

$$R_{cm}(y) = \begin{cases} R_y^c - R_y^{cm}, & \text{if } I_c(x,y) > R_y^{cm} \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where $R_y = \{R_{1,y}, R_{2,y}, ..., R_{x,y}, ..., R_{W,y}\}$ is the pixel values vector of row y of image I. $I_{x,y}$ is the pixel value at position (x,y). R_y^m is the mean value of R_y. Similarly, $R_y^c = \{R_{1,y}^c, R_{2,y}^c, ..., R_{x,y}^c, ..., R_{W,y}^c\}$ is the pixel values vector of row y of image I_c. R_y^{cm} is the mean value of R_y^c. The final salient map is obtained by combining the two row mean subtraction results, R_m and R_{cm}, which can effectively highlight regions with high intensity values and high local contrast.

$$Sal(x,y) = R_m(x,y) + R_{cm}(x,y) \tag{6}$$

To identify the salient target region, a thresholding method is used to obtain the binarized mask, M_{sal}.

$$M_{sal}(x,y) = \begin{cases} 1, & \text{if } Sal(x,y) \geq T_s \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

The threshold T_s is obtained as

$$T_s = \mu_s + \gamma\sigma_s \tag{8}$$

where μ_s and σ_s are the mean and standard deviation values of the salient map Sal; γ is a control parameter, which is set to 5 in the implementation. The region saliency detection results and the binarized mask are shown in Fig. 3(b) and Fig. 3(c), from which we can see that the proposed method can effectively highlight the ship target region.

B. Adaptive range bandwidth mean shift filtering

Mean shift smoothing algorithm is a robust feature space analysis approach, using kernel function properties to estimate gradient orientation of a point. A pixel of an image is a data point represented by two-dimensional lattice of v-dimensional vectors (pixels), where $v = 1$ for gray-level, $v = 3$ for color images, and $v > 3$ for multispectral case. Therefore, when applying the mean shift algorithm for image smoothing, a joint domain representation is used. Given a set $\{p_i\}$, $i = 1, ..., n$ of n points in the two-dimensional space, the kernel computed in the point p is defined as the product of the two domain profiles [11].

$$K_{h_s,h_r} = \frac{C}{h_s^2 h_r^v} k\left(\left\|\frac{p^s}{h_s}\right\|^2\right) k\left(\left\|\frac{p^r}{h_r}\right\|^2\right) \tag{9}$$

where $k(\|z\|)$ is called profile of the kernel $K(z)$. h_s is the spatial bandwidth, h_r is the range bandwidth, and C is a normalization constant which makes K_{h_s,h_r} to be integrated to one. For the IR images, $v = 1$. p^s and p^r are the spatial part and range part of a feature vector, respectively. In the process of mean shift filtering, the two parameters h_r and h_s are important for the performance, especially h_r. In this paper, to effectively smooth the background while protecting the ship target, we develop an adaptive range bandwidth selection method, intending to choose large range bandwidth for background region and small one for the target region.

For each pixel I_{xy} in I at location (x,y), $x = 1, ..., W; y = 1, ..., H$, a sliding window w_{xy} with size $d \times d$ centered at (x,y) is used to calculate the local standard deviation and the magnitude of the gradient. To be consistent with the mean shift smoothing process, the window size used here is the same as the mean shift kernel, that is $d = (2 \times h_s + 1)$. The spatial bandwidth h_s is chosen according to image dimensions as in [18], that is $h_s = \max\{4, [\min(H,W)/100]\}$. In the IR ship target image, the ship target region has a large standard deviation, large gradient magnitude around the boundaries and high saliency. Therefore, to protect the ship target region, the range bandwidth is associated with the local standard deviation, local gradient magnitude and the region saliency. The range bandwidth of window w_{xy} is obtained as

$$h_r(w_{xy}) = \begin{cases} h_{r0}/L_p(w_{xy}), & \text{if } M_{sal}(x,y) = 1 \\ 2h_{r0}/L_p(w_{xy}), & \text{otherwise} \end{cases} \tag{10}$$

where $L_p(w_{xy}) = L_{std}(w_{xy}) \times L_{grad}(w_{xy}) \times L_{sal}(w_{xy}) + 1$, L_{std}, L_{grad}, and L_{sal} are the local standard deviation, magnitude of the gradient, and local saliency of the processing kernel window w_{xy}. h_{r0} is a fixed initial value of h_r, which is set to 10.

From the above expression, we can see that by associating the range bandwidth with the local standard deviation, local gradient magnitude and local region saliency, a small h_r will be obtained for regions with high standard deviation, large gradient and high local saliency. These regions just correspond to the ship target regions. And for the other background regions, h_r will be large. Hence, with this adaptively selected range bandwidth, we can effectively smooth the background while preserving the ship target. Fig. 3(c) shows the smoothing results.

III. Experimental Results

A. Image smoothing results

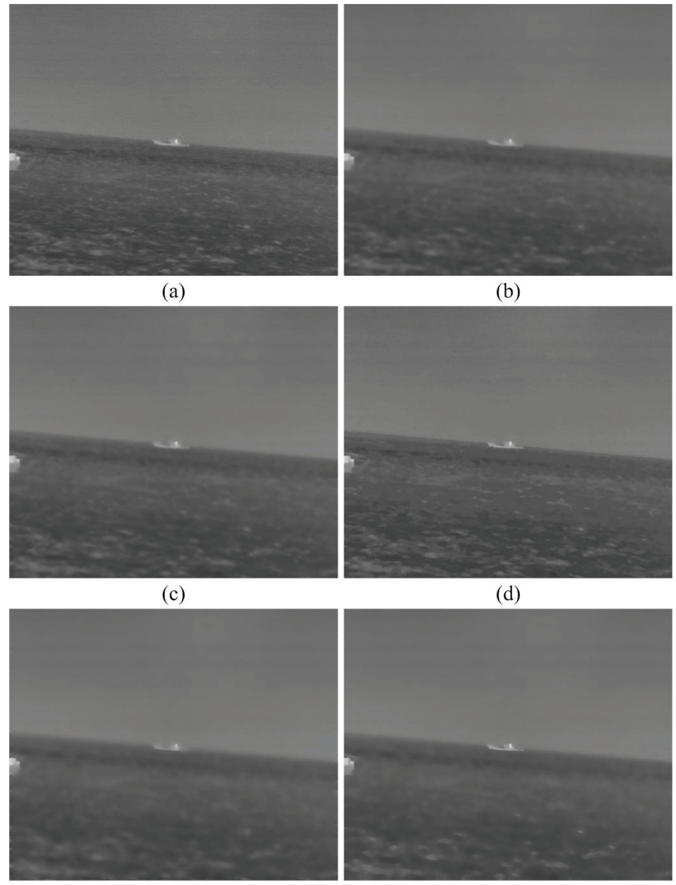
The proposed method is tested on an IR image dataset supplied by co-researchers, including 310 real IR ship target images. The images were acquired by fixed ship-borne cameras with different backgrounds, with sizes ranging from 320×256 to 720×576 pixels, which are commonly used for maritime surveillance. Parts of the experimental results are shown in Fig. 3.

Fig. 3(a) shows the original IR images, and Fig. 3(b) and Fig. 3(c) show the salient region detection results and the binarized mask, and Fig. 3(d) shows the final smoothing results.

From Fig. 3(b) and Fig. 3(c) we can see that with the proposed salient region detection method, the ship target regions are well identified with high saliency while the background regions are suppressed. This result can be used for the target preservation during the following smoothing process. Fig. 3(d) shows that the proposed method works well for IR images with different ship targets and backgrounds. After the filtering we obtain well smoothed images, in which most of the background noises are removed and the ship target regions are well preserved.

B. Comparison results

1) Visual comparison: To illustrate the effectiveness of the proposed method, comparisons are made with other four methods, including the anisotropic diffusion filtering (Anisotropic) [8], the bilateral filtering (Bilateral) [9], the Kuwahara filtering (Kuwahara) [10], and the mean shift filtering with fixed range bandwidth (Mean shift) [11]. To make the comparison reasonable, we tried to obtain the best possible result by tuning the relevant parameters, including the number of iteration num_{iter} and the gradient modulus threshold t used in the anisotropic diffusion filtering, the half-size of the filtering window w and the standard deviations σ used in the bilateral filtering, the kernel bandwidth parameter L of the Kuwahara filtering, and the range bandwidth h_r of the mean shift filtering. Comparison results on different IR images are shown in Figs. 4 - 7.

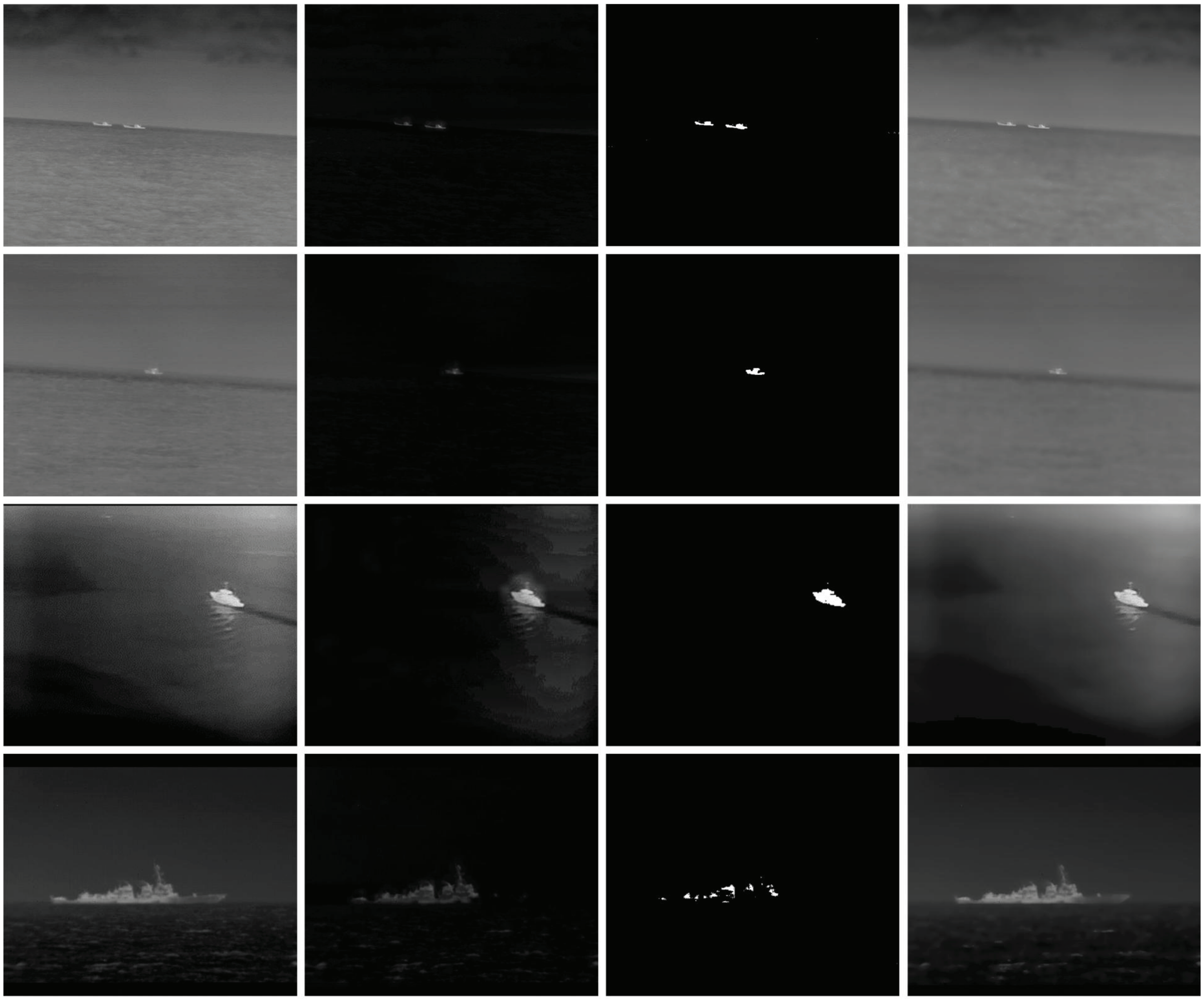


(a) (b) (c) (d) (e) (f)

Fig. 4. Comparison results of IR image with complex sea clutters. (a) The original IR image; (b) The result of anisotropic diffusion filtering (num_{iter} =15, t =10); (c) The result of bilateral filtering (w=5; σ=[3, 0.1]); (d) The result of Kuwahara filtering (L=1); (e) The result of mean shift filtering with fixed range bandwidth (h_r=35); (f) The result of the proposed method.

Fig. 4 shows the comparison results of an IR image with heavy sea clutters. From Fig. 4(b) and Fig. 4(c) we can see that the performances of the anisotropic diffusion filtering and the bilateral filtering method are similar. Both methods can smooth some background noises. However, they are unable to completely suppress the heavy sea clutters, and the edges of the ship target region are blurred. From Fig. 4(d) we can see that the Kuwahara filtering method can preserve the boundaries of the ship target from smoothing, but it fails to suppress the sea clutters and it causes serious block artefacts. From Fig. 4(e) we can see that with the fixed range bandwidth, the mean shift filtering method can effectively suppress the heavy sea clutters; however, the boundaries of the ship target are also smoothed. With a smaller fixed range bandwidth, the ship target region can be well preserved, but the background cannot be well suppressed. Therefore, for the mean shift method with fixed bandwidth, it is difficult to choose a proper bandwidth. Note that in our experiments, we tried to choose a range bandwidth that can balance the smoothing of background and the preservation of the target region. Fig. 4(f) shows that with the proposed method, we can effectively suppress the complex sea clutters around the ship target region, and also protect the ship target region from being smoothed. Fig. 4 demonstrates that the proposed method produces better results than the other methods for IR images with complex sea clutters.

Fig. 5 shows the comparison results of an IR image with low contrast. From Fig. 5(a) we can see that the ship target is small and embedded in sky and sea backgrounds with low contrasts. From Fig. 5(b) we can see that the anisotropic diffusion filtering method does not work well for this image. It seriously blurs the ship target and the sea background is not well suppressed. Fig. 5(c) shows that bilateral filtering has a better performance than the anisotropic diffusion filtering. This method can effectively smooth the sea background and protect most of the ship target region from smoothing. However, the edges of the ship target are still blurred with this method. It can be seen from Fig. 5(d) that the Kuwahara filtering method excessively smooths the ship target region. Although this method can suppress most of the sea background clutters, it causes serious block artefacts. From Fig. 5(e) and Fig. 5(f) we can see that the performances of the fixed range bandwidth and the proposed adaptive range bandwidth are comparable. Both of them obtain a good smoothing result. The backgrounds are



(a) (b) (c) (d)

Fig. 3. Image smoothing result. (a) The original IR image; (b) The salient region map; (c) The binarized mask; (d) The smoothed image.

well suppressed and the ship target regions are well preserved. The results of Fig. 5(e) and Fig. 5(f) indicate that the adaptive range bandwidth selection method is effective; and with the proposed method, we can automatically choose a good range bandwidth for image smoothing.

Fig. 6 shows the comparison results of IR images with high contrast and uneven background. From Fig. 6(a) we can see that the IR image is degraded with background noises. From Fig. 6(b) to Fig. 6(f) we can see that except for the Kuwahara filtering method (Fig. 6(d)), all the other methods can successfully remove the background noises and obtain a smooth image. The anisotropic diffusion filtering and the bilateral filtering yield similar results (Fig. 6(b) and Fig. 6(c)), and both methods blur the upper part structure of the ship target while smoothing. The Kuwahara filtering method can well preserve the upper structure of the ship target; however, the block artefacts still exist. The performance of the fixed mean shift and the proposed method are similar, which can effectively smooth the background while protecting the ship target structures. The results also validate the effectiveness of the proposed adaptive range bandwidth selection method.

Fig. 7 shows the comparison results of IR image containing a large ship target with uneven intensities. Fig. 7(b) shows the smoothing result of the anisotropic diffusion filtering method, from which we can see that the whole image is blurred with this method. It can not successfully suppress the sea background and protect the ship target region. Fig. 7(c) shows the result of the bilateral filtering, from which we can see that the bilateral filtering performs better than the anisotropic diffusion filtering method. The bilateral filtering method can suppress most of the sea background clutters and most of the ship target regions are well preserved. However, there are still slightly over smoothing around the boundaries of the ship target. Fig. 7(d) shows the Kuwahara filtering result. This method can well preserve the structure of the ship target, and most of the sea background clutters are suppressed. However, there are still some block artefacts that need to be removed. Fig. 7(e) and Fig. 7(f) show the results of mean

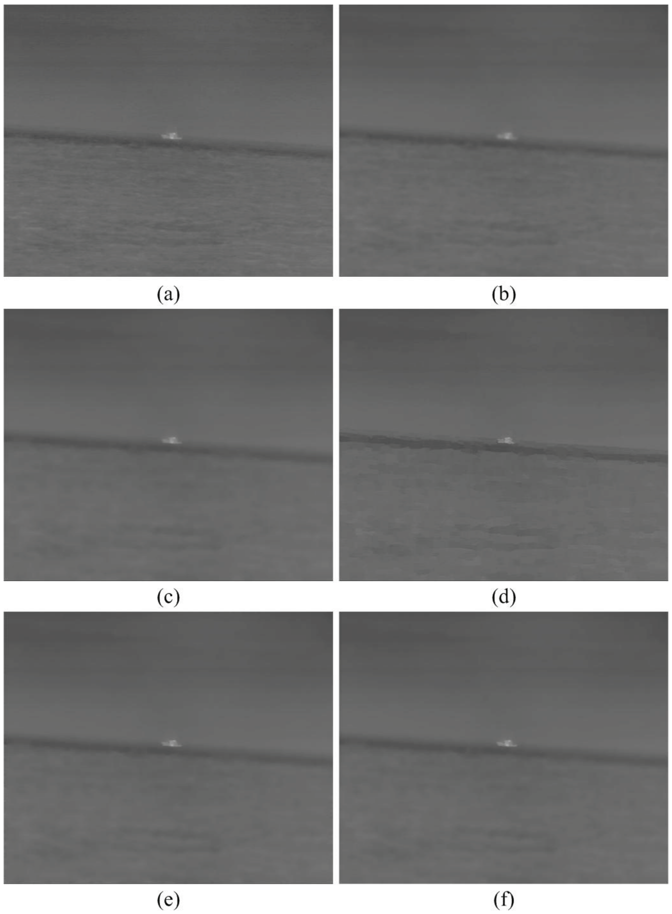


Fig. 5. Comparison results of IR image with low contrast. (a) The original IR image; (b) The result of anisotropic diffusion filtering (num_{iter} =10, t =15); (c) The result of bilateral filtering (w=9; σ=[5, 0.05]); (d) The result of Kuwahara filtering (L=3); (e) The result of mean shift filtering with fixed range bandwidth (h_r=15); (f) The result of the proposed method.

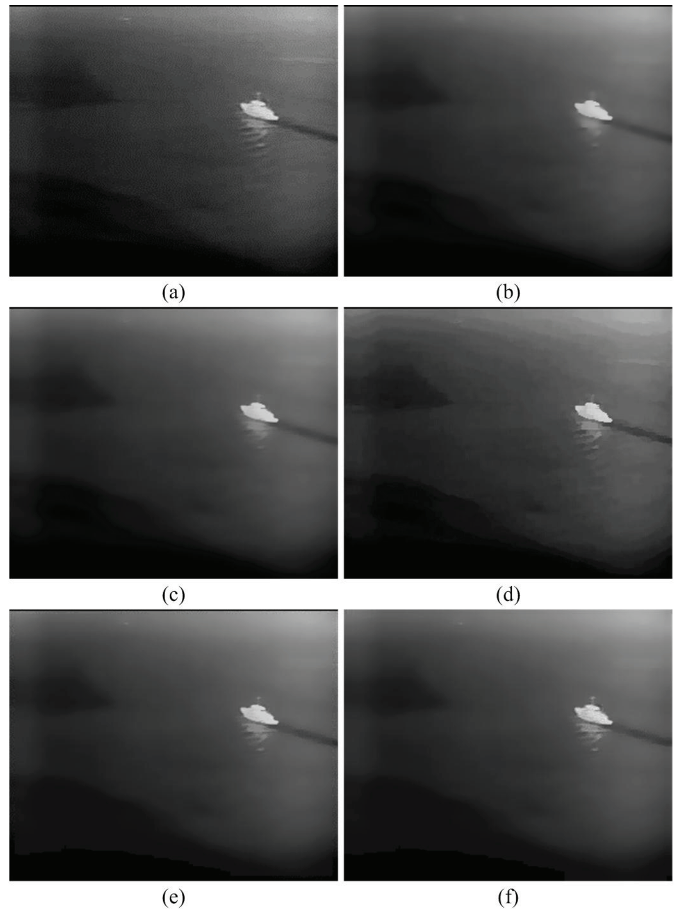


Fig. 6. Comparison results of IR image with uneven high contrast background. (a) The original IR image; (b) The result of anisotropic diffusion filtering (num_{iter} =15, t =10); (c) The result of bilateral filtering (w=5; σ=[5, 0.1]); (d) The result of Kuwahara filtering (L=1); (e) The result of mean shift filtering with fixed range bandwidth (h_r=30); (f) The result of the proposed method.

shift filtering with fixed range bandwidth and the proposed adaptive range bandwidth. From Fig. 7(e) and Fig. 7(f) we can see that, both the two methods can effectively suppress the background. However, some details of the ship target are also smoothed using the mean shift filtering method with fixed range bandwidth, while the proposed method can well protect the ship target structure.

From the comparison results in Figs. 4 - 7 we can see that in all cases the proposed method outperforms the other competitive methods. Therefore, it can be concluded that the proposed adaptive range bandwidth mean shift filtering is effective, and it demonstrates a superior performance for IR ship target smoothing.

2) Quantitative comparison: To further verify the effectiveness of the proposed method, quantitative evaluation is performed. As the reference standard images are unavailable, so the quantitative evaluation with references can not be used. In this paper, we take three non-reference measures for performance analysis, edge based contrast measurement (EBCM) [19], equivalent number of looks (ENL), and speckle suppression index (SSI) [20]. EBCM measures the local contrast of each pixel (x, y), as defined in [19]

$$EBCM_{xy} = \frac{|X_{xy} - \overline{E}_{xy}|}{|X_{xy} + \overline{E}_{xy}|} \tag{11}$$

where X_{xy} is the pixel value at the position of (x, y). $\overline{E}_{xy}$ is the mean edge grey level of each window W_{xy} centered at (x, y), which is defined by

$$\overline{E}_{xy} = \left(\sum_{(m,n)\in W_{xy}} \Delta_{mn} \cdot X_{mn}\right) \Bigg/ \left(\sum_{(m,n)\in W_{xy}} \Delta_{mn}\right) \tag{12}$$

where Δ_{mn} is the edge value of each pixel (m, n) belonging to W_{xy}. In this implementation, the edge value is computed using the Sobel operator. A higher value of EBCM indicates a higher local contrast associated to each pixel in a given neighborhood.

ENL measures the quality of the filtered image, as defined in [20]

$$ENL = \left(\frac{Mean_f}{Std_f}\right)^2 \tag{13}$$

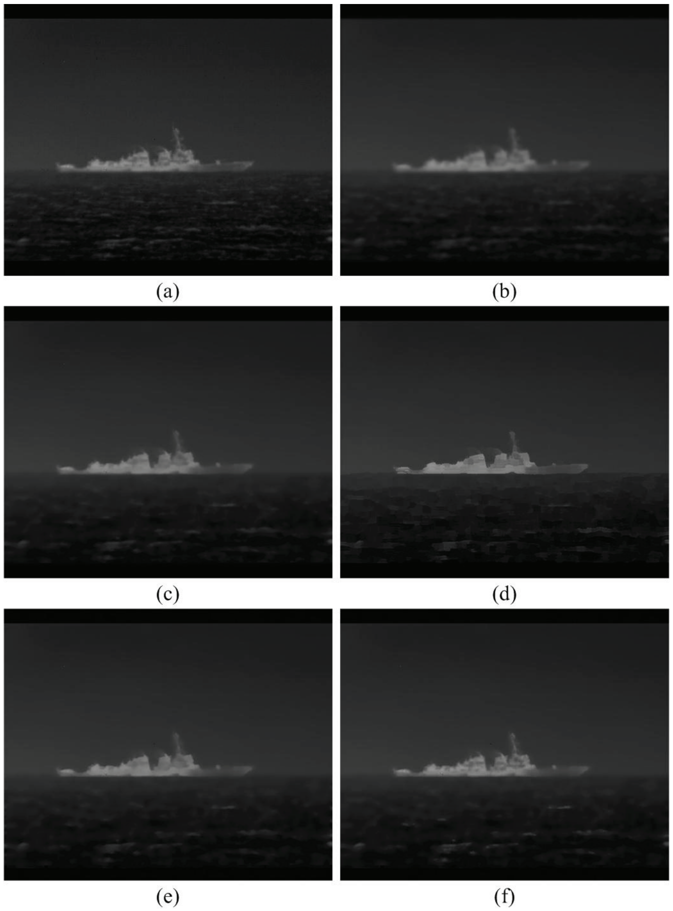


Fig. 7. Comparison results of IR image with uneven ship target. (a) The original IR image; (b) The result of anisotropic diffusion filtering (num_{iter} =15, t =15); (c) The result of bilateral filtering (w=9; σ=[5, 0.05]); (d) The result of Kuwahara filtering (L=3); (e) The result of mean shift filtering with fixed range bandwidth (h_r=20); (f) The result of the proposed method.

where $Mean_f$ and Std_f are mean and standard deviation values of the filtered image, respectively. A larger ENL value means a better performance of the filter.

As speckle noise is one important kind of noises needs to be removed, we take the SSI as another measurement. SSI is defined as the ratio of coefficient of the variance of the filtered image to the coefficient of variance of the original image, as expressed below [20]

$$SSI = \frac{\sqrt{Var_f}}{Mean_f} \times \frac{\sqrt{Var_o}}{Mean_o} \tag{14}$$

where $Mean_f$ and Var_f are the mean and variance values of the filtered image, and $Mean_o$ and Var_o are the mean and variance values of the original image. The smaller value of SSI means a higher suppression of speckle noise. The quantitative evaluation results with the average EBCM, ENL, and SSI are shown in Table I.

From Table I, we can see that in terms of EBCM, ENL, and SSI, the proposed method gives better performance than the other four methods. The proposed method obtains a higher average EBCM, a higher average ENL, and a lower average

TABLE I
QUANTITATIVE EVALUATION RESULTS.

Methods	EBCM	SSI	ENL
Anisotropic	3.5165	0.9641	43.8883
Bilateral	3.6984	0.9634	44.6694
Kuwahara	3.8474	0.9860	42.1252
Mean shift	3.7511	0.9482	44.4414
Proposed method	4.1813	0.9118	56.2123

SSI, indicating that the proposed method is effective for noise suppression and can obtain a filtered image with high local contrast and high quality.

IV. Conclusion

An effective smoothing method for IR ship target images is proposed in this paper. First, based on the local region properties, we develop a salient region detection method to highlight the ship target region, which is important for ship target protection during the smoothing process. Then, by associating the range bandwidth with the local region saliency, standard deviation and gradient magnitude, we propose an adaptive range bandwidth selection method for the mean shift filtering. Experimental results show that the proposed method works well for IR ship target images. Comparison results with other edge preserving filtering methods demonstrate that the proposed method performs better for IR images with different backgrounds, and it can effectively suppress background noises while preserving ship target regions. This is useful for many applications, such as IR ship target segmentation, target detection, and recognition.

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