BILATERAL EDGE DETECTORS

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ABSTRACT

We propose to employ bilateral filters to solve the problem of edge detection. The proposed methodology presents an efficient and noise robust method for detecting edges. Classical bilateral filters smooth images without distorting edges. In this paper, we modify the bilateral filter to perform edge detection, which is the opposite of bilateral smoothing. The Gaussian domain kernel of the bilateral filter is replaced with an edge detection mask, and Gaussian range kernel is replaced with an inverted Gaussian kernel. The modified range kernel serves to emphasize dissimilar regions. The resulting approach effectively adapts the detection mask according as the pixel intensity differences. The results of the proposed algorithm are compared with those of standard edge detection masks. Comparisons of the bilateral edge detector with Canny edge detection algorithm, both after non-maximal suppression, are also provided. The results of our technique are observed to be better and noise-robust than those offered by methods employing masks alone, and are also comparable to the results from Canny edge detector, outperforming it in certain cases.

***Index Terms*—** Bilateral filters, edge detection, domain kernel, range kernel, edge detection masks.

1. INTRODUCTION

Edge formation in images can be attributed to either geometric or non-geometric events. Geometric events include object and surface borders, and non-geometric events comprise shadows, reflections, and specularity. Curvatures, contours, and corners of images represent important features in an image. The popularity of these features in various higher-level computer vision algorithms stems from the fact that a major portion of the information content of the image lies in them. This necessitates a reliable and efficient extraction of these features, which in turn demands an efficient edge detection algorithm.

Over the years, there has been considerable interest in developing robust edge detection algorithms. One basic approach to edge detection makes use of derivatives. There are mainly two variants of derivative-based techniques: (a) gradient-based methods, and (b) Laplacian-based methods. Gradient operation is approximated in digital images using an orthogonal pair of standard masks. Some of the popular gradient masks used in the literature include the Sobel [1], Roberts [2], and Prewitt masks [3]. The gradient methods give superior results in images with abrupt transitions in gray-level values. For smoother gray-level transitions, the Laplacian-based methods offer a better alternative [4].

However, the usage of differential masks presents practical difficulties, as the derivative operation acts as highpass filter, which amplifies noise. To overcome this problem, the image needs to be smoothed with a low pass filter. Consequently, edge detectors such as Laplacian of Gaussian (LoG) [5] have been proposed, which significantly reduce the effect of noise. On the flip side, the disadvantage of using LoG mask is that the orientation of edges cannot be determined.

A popular and widely used method is the Canny edge detection algorithm [6], which pre-filters the image to maximize the signal-to-noise ratio. This is followed by gradient computation to emphasize regions with high spatial variations. Pruning of edges is then achieved by non-maximal suppression. The gradient array is further reduced by hysteresis edge linking, which suppresses edge points that are not linked, by using proper thresholds.

1.1. Related work

Bilateral filtering is a technique to smooth images without smearing the edges. An initial effort in this direction began with the work of Aurich and Weule [7] who employed nonlinear modifications of Gaussian filters. The current form of the nonlinear implementation of bilateral filters was introduced by Tomasi and Manduchi [8]. Elad [9] underlined the theoretical connection of the bilateral filter with classical techniques, proving that it can be derived as a result of a Bayesian estimation problem. Bilateral filtering has been put to use in varied image processing applications such as texture separation [10], tone mapping [11], illumination compensation [12], etc. A major constraint of bilateral filtering is computational load and there has been considerable interest in developing faster implementations. Porikli [13] explored ways of improving the computational efficiency of the bilateral filtering operation. Paris and Durand [14] exploited downsampling in space and intensity to come up with a fast approximation of the bilateral filter. Another major contribution in the same direction was made by Chaudhury et al. [15], who proposed a constant-time algorithm for fast bilateral filtering using trigonometric range kernels. Peng and Rao [16], Kishan and Seelamantula [17] proposed to optimally choose the bilateral filter parameters within a risk-estimation framework, so as to improve denoising performance.

However, there has not been much research aimed at exploring the employability of bilateral filters for edge detection, to the best of our knowledge. Bilateral filtering has been used as a pre-processing step before standard edge detection techniques [18]. A direct application of bilateral filters for edge detection was done by Hankamer et al. [19] who calculated photometric weights based on the spatial intensity variations in images.

Our interest is to explore whether the edge-preserving standard bilateral filter can be so modified as to perform the task of highlighting edges. We motivate the employability of bilateral filters for different feature extraction tasks, before proceeding with the specific topic of edge detection. In this paper, we propose to detect edges

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by a proper choice of the range and domain kernels of the classical bilateral filter. We show that a robust bilateral edge detector can be designed by selecting a domain kernel that performs a derivative operation, and a range kernel that adaptively accentuates its highpass effect at edges. Standard edge detection masks and an inverted Gaussian kernel come out naturally as candidates for the domain and range kernels, respectively.

The rest of the paper is organized as follows. The proposed method of bilateral edge detection is detailed in Section 2, followed by some results and comparisons with existing methods in Section 3. Concluding remarks are drawn in Section 4.

Notations: Image value at pixel position $\mathbf{a}$ is denoted by $I(\mathbf{a})$. The set $\mathcal{D}$ is used to denote possible image locations in the spatial domain of a mask. We use $|\cdot|$ for the absolute value and $\|\cdot\|$ for the Euclidean distance.

2. BILATERAL EDGE DETECTORS

2.1. Standard bilateral filter

Classical bilateral filtering is a nonlinear technique that smoothes an image while preserving the edges. The bilateral filtering operation is carried out on the spatial neighborhood of a pixel using domain and range kernels. The domain kernel, aimed at smoothing the image, is a Gaussian function, which weighs pixels depending on the spatial distance from the central pixel at location $\mathbf{a}$. Edge preservation is achieved by means of the range kernel, which takes into account the radiometric distance of the pixels from the central pixel. Thus, adaptive smoothing of the image is accomplished by taking the intensity variations into consideration. The domain kernel is given by the equation

$$Y_{\sigma_\mathrm{d}} = \exp\left(\frac{-(\|\mathbf{a}-\mathbf{b}\|^2)}{2\sigma_\mathrm{d}^2}\right), \tag{1}$$

and the range kernel is

$$Y_{\sigma_\mathrm{r}} = \exp\left(\frac{-(|I(\mathbf{a})-I(\mathbf{b})|)^2}{2\sigma_\mathrm{r}^2}\right). \tag{2}$$

From (1) and (2), it is clear that the domain kernel depends on spatial distance between pixels, that is, $\|\mathbf{a}-\mathbf{b}\|$, and the range kernel depends on the intensity difference between the pixels, $|I(\mathbf{a})-I(\mathbf{b})|$. Gaussian filtering operation by using the domain kernel is given by

$$\mathbf{Y}_{\mathrm{GF}} = \sum_{\mathbf{b}\in\mathcal{D}} Y_{\sigma_\mathrm{d}} I(\mathbf{b}). \tag{3}$$

In bilateral filtering, along with the domain filtering (cf. (3)), a range kernel is incorporated to preserve edges in the output. The bilaterally-filtered result is given as follows:

$$\mathbf{Y}_{\mathrm{BF}} = w_{\mathbf{a}}^{-1} \sum_{\mathbf{b}\in\mathcal{D}} Y_{\sigma_\mathrm{r}} Y_{\sigma_\mathrm{d}} I(\mathbf{b}), \tag{4}$$

where $w_{\mathbf{a}}$ is the normalization factor, which makes pixel weights sum to 1 and is given by

$$w_{\mathbf{a}} = \sum_{\mathbf{b}\in\mathcal{D}} Y_{\sigma_\mathrm{r}} Y_{\sigma_\mathrm{d}}. \tag{5}$$

2.2. Proposed edge detector

The idea behind the proposed method is to suitably choose the domain and range kernels so as to emphasize edges in images. In standard bilateral filters, the objective is one of smoothing while preserving the edges, the twin requirements being satisfied using (i) a smoothing domain kernel, and (ii) a range kernel that attaches lower weights to pixels of large intensity difference. Employing Gaussian functions as domain and range kernels serves to achieve this goal. The point to be noted here is that different bilateral operators such as edge detector, directional smoother, etc., can be realized by properly selecting the range kernel in accordance with the filtering action of the domain kernel. In the present work, our goal is to design a bilateral edge detector, which demands the following conditions to be satisfied:

1. Edges correspond to high frequency content in an image. Thus, we require a domain kernel that performs derivative operation.
2. The range kernel must be such that it attaches weights varying directly as the pixel intensity difference, so that it emphasizes dissimilar regions.

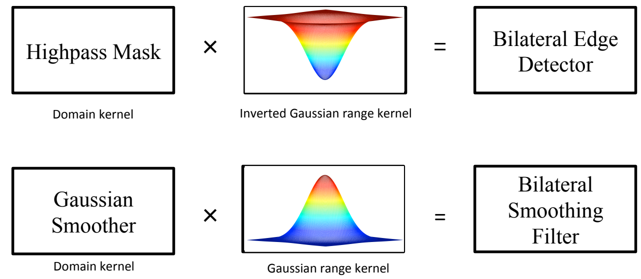

Fig. 1. (Color in electronic version) Block diagram representation of the bilateral edge detector and the standard bilateral smoothing filter.

A domain and range kernel pair that assists in satisfying the above two conditions is the one employing a highpass domain kernel (such as the Sobel, Prewitt, Roberts, Laplacian or LoG masks) and an inverted Gaussian range kernel. This results in the standard domain kernel masks becoming adaptive based on the image intensity values, which leads to more robust edge detection than what could be achieved with fixed weights of highpass masks. Also, as we show in the experimental results section, the resulting operator accurately detects edges even when there is only a gradual change in intensity values and in presence of noise. A block diagram representation, wherein we compare the classical bilateral filter with the proposed approach, is shown in Fig. 1. The modified range kernel is given as follows:

$$G_{\sigma_\mathrm{r}} = 1 - \exp\left(\frac{-(|I(\mathbf{a})-I(\mathbf{b})|)^2}{2\sigma_\mathrm{r}^2}\right). \tag{6}$$

Another desirable property for the range kernel is that it should never become zero at any point, because if it does, the effect of the domain kernel would be nullified at those points resulting in improper filtering action. We would like to carry this property, which is satisfied by the range kernel chosen in the standard bilateral filter, over to the case of the bilateral edge detector as well. Note that with the range kernel chosen as in (6), a zero weight would be associated with the central pixel. The problem may be circumvented by introducing a small bias in (6) as shown below:

$$G'_{\sigma_\mathrm{r}} = 1.1 - \exp\left(\frac{-(|I(\mathbf{a})-I(\mathbf{b})|)^2}{2\sigma_\mathrm{r}^2}\right). \tag{7}$$

Usually, edges obtained using gradient masks are thick. To produce localized and thin edges, the result of the bilateral edge detector can be fed to a non-maximal suppression block to retain only the pixels that are locally maximum along the gradient direction.

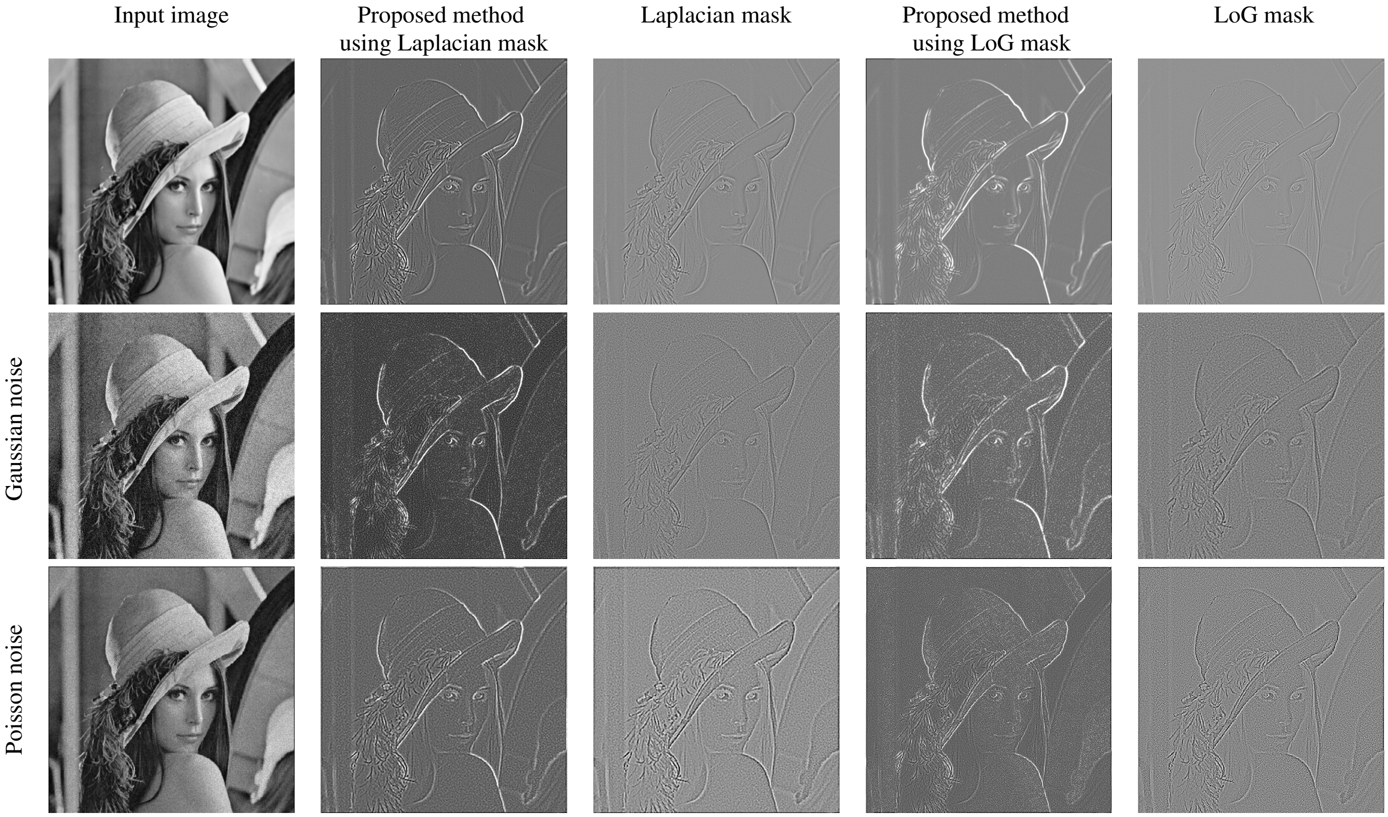

Fig. 2. Performance comparison of bilateral edge detector using Laplacian and LoG domain kernels versus standard edge detectors using corresponding masks alone. First row - Results on clean image, second and third rows - Results in presence of Gaussian (PSNR: 20.17 dB) and Poisson noise (PSNR: 27.54 dB), respectively.

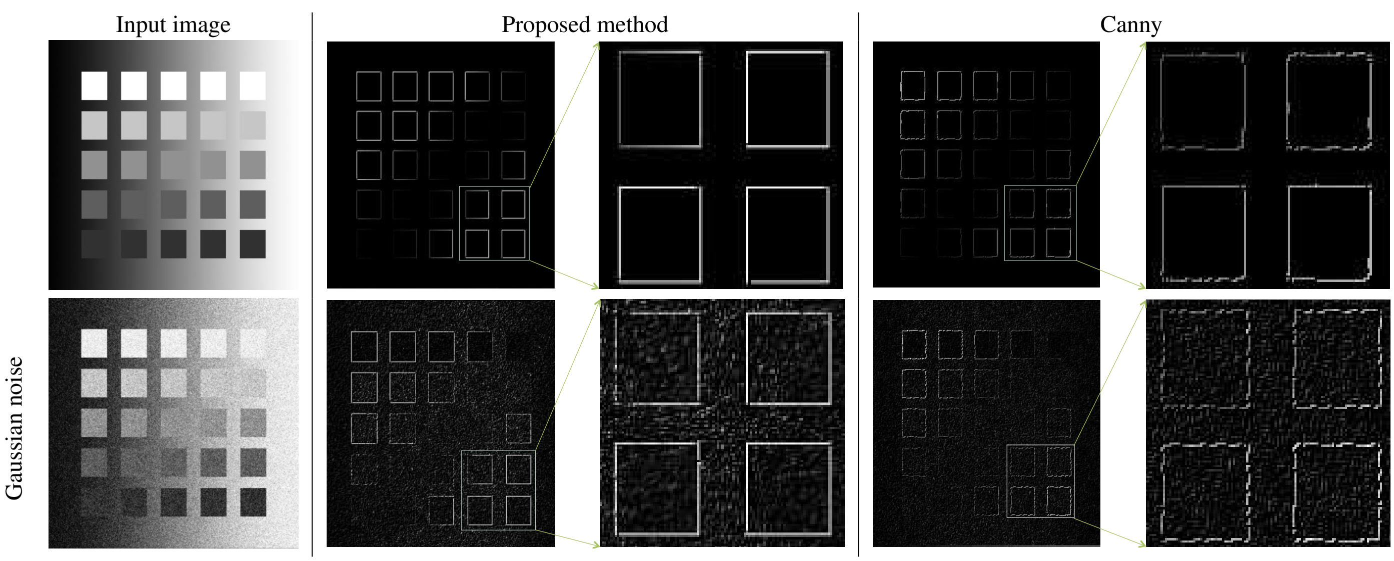

Fig. 3. Performance comparison of bilateral edge detector using Sobel domain kernel versus Canny edge detector, both after non-maximal suppression on Bartleson image without (first row) and with Gaussian noise (second row, PSNR: 20.39 dB).

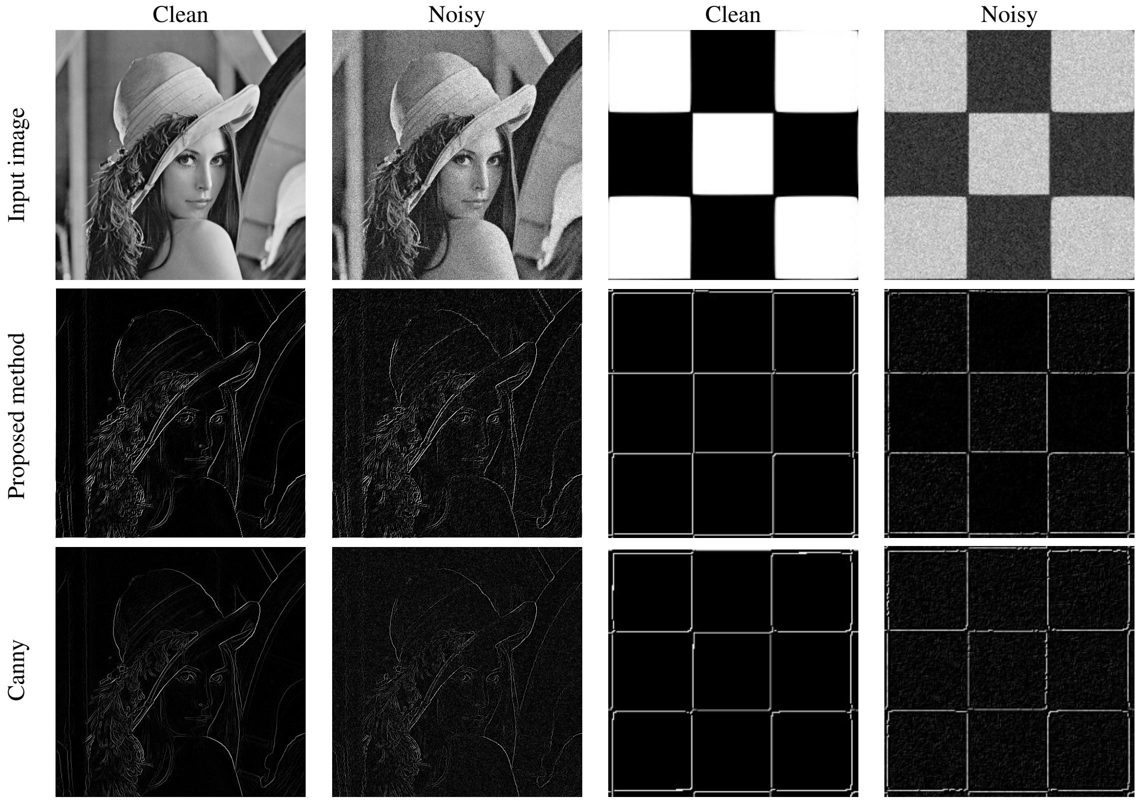

Fig. 4. Performance comparison of bilateral edge detector using Sobel domain kernel versus Canny edge detector, both after non-maximal suppression on Lenna and Checkerboard images without and with Gaussian noise (Lenna-PSNR: 20.17 dB, Checkerboard-PSNR: 20.23 dB).

3. EXPERIMENTAL RESULTS

We present some results on standard test images, comparing the performance of the proposed bilateral filter-based edge detection technique with other standard methods. In each case, we present the results with both clean and noisy inputs, the latter aimed at assessing the noise robustness of the techniques.

3.1. Comparison with standard edge detection masks

Presently, we compare the performance of methods making use of standard edge detection masks (Laplacian and LoG) with the bilateral edge detector using the corresponding mask as domain kernel, on the Lenna image. The results obtained in case of the Laplacian and LoG masks are shown in Fig. 2. The first row in each case corresponds to the results on the clean image, the second row corresponds to that obtained on a noisy image to which Gaussian noise of standard deviation 25 was added, and the third row shows results obtained on images corrupted by Poisson noise. The results suggest that the proposed method takes into account the intensity gradation in the input image, leading to corresponding gradation in the resultant edges. In presence of noise, however, we note that the proposed method highlights edges prominently.

3.2. Comparison with the Canny edge detector

We considered the standard Lenna, Bartleson (which illustrates the Bartleson-Breneman effect [20], that is, the perceived contrast between identical squares changes based on the variation in intensity of background), and Checkerboard images, and performed edge detection using the proposed method using Sobel mask as the domain kernel, and the Canny edge detector, both employing non-maximal suppression. The results obtained are depicted in Fig. 3 and Fig. 4. We observe that the proposed technique results in perfect vertical and horizontal edges in case of Bartleson and Checkerboard images, whereas the output of the Canny algorithm exhibits breaks and kinks. This aspect is made clear in the zoomed-in versions of the results in Fig. 3. Also, the Canny output degrades slightly in presence of noise, whereas the bilateral edge detector seems to be more robust to noise. The results on the Lenna image (cf. Fig. 4) are comparable to those obtained from the Canny detector.

4. CONCLUSIONS

We addressed the problem of edge detection using bilateral filters. The classical bilateral filter was modified for edge detection using appropriate domain kernel masks and an inverted Gaussian range kernel. The algorithm was validated on standard images and the results were compared with Canny edge detector with non-maximal suppression and edge detection using standard masks. Choosing the variance of the inverted Gaussian kernel optimally as dictated by the variance of the noise corrupting the image as in [17], developing a computationally less intensive version of the algorithm, and subsequently evaluating the performance of the bilateral edge detector are future research directions.

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