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(Research Article)

Exploring the Effectiveness of Sobel, Canny, and Prewitt Edge Detection Algorithms on Digital Images

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Abstract

Edge detection is a fundamental process in image processing, crucial for identifying object boundaries and structural features within images. This study explores three classical edge detection techniques - Canny, Sobel, and Prewitt. Six test images were used to ascertain their performance based on five metrics: Recall, Precision, F1-Score, Structural Similarity Index (SSIM), and Figure of Merit (FoM) implemented using python. The experimental results indicate that the Canny operator consistently outperforms the others in terms of Recall, F1-Score, and FoM, demonstrating superior capability in detecting true edges with high sensitivity and robustness against noise. The Sobel operator achieves the highest Precision and SSIM scores, reflecting strong edge localization and structural preservation, although with lower overall edge detection effectiveness. The Prewitt operator offers balanced performance across all metrics, providing a compromise between detection quality and computational simplicity. These findings are consistent with general observations from the literature, where Sobel is recognized for its noise resistance and simplicity, making it suitable for fast, real-time applications, while Prewitt, offering a similarly straightforward implementation, exhibits slightly greater sensitivity to noise. The Canny operator, widely regarded as the optimal edge detector, remains the preferred method for applications requiring high precision, low error rates, and strong edge continuity. Consequently, Canny is best suited for high-accuracy edge detection tasks, Sobel excels in structure-preserving applications, and Prewitt is recommended for general-purpose, resource-constrained scenarios.

Keywords: Edge Detection; Sobel; Prewitt; Canny; Image Processing; Image Segmentation

1. Introduction

In digital image processing, Edge detection is a fundamental step in object preprocessing. To isolate an image from its background and neighbouring images, the edges need to be recognized. An edge in an image is an image contour across which the image's brightness or hue changes abruptly, perhaps in the magnitude [1]. These edges often correspond to the outlines of objects, surface markings, or discontinuities in depth. Thus, edge detection identifies and locates the boundaries or edges of objects in an image. It is used to identify and detect the discontinuities in the image intensity and extract the outlines of objects present in an image [2]. Its primary goal is to simplify image representation while preserving its essential structural features. With this process, it is easier to detect object boundaries, segment regions of interest in an image and extract meaningful features for further analysis. Edge detection is indispensable in various applications, such as object recognition, scene understanding, and image segmentation. They can be applied in Computer Vision as a fundamental process in facial recognition, motion detection, and 3D reconstruction. It helps machines interpret and understand visual data in a way similar to how humans do. In Medical Imaging; Doctors use edge detection to highlight structures in X-rays, MRIs, and CT scans. This helps in diagnosing conditions more accurately.

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Self driven cars equipped with cameras use edge detection to identify lanes, obstacles, and traffic signs, ensuring safe navigation. More so, Image Editing Software like Photo shop and other editing applications utilize edge detection to allow users make precise selections and enhancements. There are four steps in edge detection. These include :

- Smoothing: suppresses as much noise as possible, without destroying the true edges.
- Enhancement: this entails applying a filter to enhance the quality of the edges in the image (sharpening).
- Detection: determines which edge pixels should be discarded as noise and which should be retained (usually, thresholding provides the criterion used for detection).
- Localization: determines the exact location of an edge (sub-pixel resolution might be required for some applications, that is, estimate the location of an edge to better than the spacing between pixels). Edge thinning and linking are usually required in this step.

Various edge detection algorithms had been developed over the years, each with its strength and applications. However, the Sobel, Prewitt, and Canny operators are widely used due to their balance between effectiveness and computational efficiency. The Sobel and Prewitt operators are gradient-based methods that detect edges by computing intensity differences in an image . This is achieved by finding the maximum and minimum values of the image's first derivative. These methods are simple and computationally efficient but are highly sensitive to noise, leading to false edge detection in low-quality images [3]. On the other hand, the Canny edge detector employs Gaussian based technique as well as gradient based technique. This is a multi-stage process, including noise reduction using Gaussian filter , gradient calculation , and edge tracking, making it more robust in detecting edges with minimal false positives. More so, Studies have shown that the Canny operator provides better edge continuity, higher precision, and reduced sensitivity to noise compared to Sobel and Prewitt, though at the cost of increased computational complexity [4] [5] [6]

2. Related Literature

Several researchers have evaluated classical operators like Sobel and Prewitt for basic edge detection tasks. The study in [7] evaluated various edge detection operators and observed that while Sobel and Prewitt were computationally efficient, they were sensitive to noise and less effective in preserving fine edges compared to newer techniques. The concept of gravitational field intensity to replace image gradient was proposed in [8]. Two adaptive threshold selection methods based on the mean of image gradient magnitude and standard deviation were put forward for two kinds of typical images (one has less edge information, and the other has rich edge information) respectively. Results showed that the algorithm preserve more useful edge information and more robust to noise. One study [5] compared the performance of Sobel, Prewitt, and Canny edge detectors using different image formats. The results showed that while Sobel and Prewitt are faster and simpler, Canny generally provides more accurate edge detection due to its edge localization and noise reduction capabilities. This study highlights the trade-off between simplicity and accuracy in choosing an appropriate edge detection algorithm. In medical imaging, [9] applied Sobel and Prewitt operators for detecting edges in MRI scans. They observed that while Sobel produced sharper edges, Prewitt provided smoother transitions, although both suffered under noisy conditions. Canny detector significantly improved edge detection accuracy in face recognition systems compared to Sobel and Prewitt. [10]. Compared to the Sobel algorithm, Canny's edge detection approach yields much lower memory requirements, reduced latency, and enhanced throughput without sacrificing edge detection performance [11]. More so, , in the domain of remote sensing; Canny, Sobel, and Prewitt operators were compared for edge detection in satellite images. Their results highlighted that Canny achieved better localization and detection of meaningful edges, crucial for feature extraction in remote sensing applications [12].

3. Materials and Methods

The edge detectors used in this paper are analysed in this section:

3.1. Sobel Edge detection:

The Sobel Operator involves estimating the first derivative of an image [3] by applying a convolution process between an image (i.e. the input) and two special masks of 3 X 3 kernel, one to detect vertical edges given as

$$\begin{pmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{pmatrix}$$

and another to detect horizontal edges given as

$$\begin{pmatrix} -101 \\ -202 \\ -101 \end{pmatrix}$$

The Procedure:

i. These masks are each convolved with the image.

ii. At each pixel location (x,y) there are two values: ,

$G_x$corresponding to the result from the row mask and $G_y$from the column mask.

iii. G_x,G_y are used to compute two matrices, the edge magnitude and the edge direction (angle of orientation of the edge) at pixel(x,y) defined as:

$$\text{Edge Magnitude} = \sqrt{\text{Gx}^2+\text{Gy}^2}$$

$$\text{and Edge direction} = \tan^{-1}\left(\frac{\text{Gx}}{\text{Gy}}\right)$$

Where;

G_x; The gradient in the y-direction
G_y; The gradient in the x-direction

3.2. Prewitt Edge Detection

Similar to Sobel, Prewitt is gradient-based. However, it assigns equal weight to all pixels unlike Sobel that places more emphasis on the central pixel by using a weightier value [14] The kernel for Prewitt is given as:

$$G_y = \begin{pmatrix} -1 & -1 & -1 \\ 0 & 0 & 0 \\ 1 & 1 & 1 \end{pmatrix}\text{; for the vertical edges.}$$

And

$$G_x = \begin{pmatrix} -101 \\ -101 \\ -101 \end{pmatrix}\text{; for the horizontal edges.}$$

Again, these masks are each convolved with the image just as in Sobel.

3.3. Canny edge detection

Canny edge detection operator is an edge detection technique developed by John F. Canny in 1986. The canny operator in the edge detection process uses a Gaussian filter to reduce noise and false edge detection [13]. Basic steps in canny edge detection algorithm include:

3.3.1. Smoothing the input image using Gaussian filter

Let f(x,y) denote the input image and G(x,y) denote the Gaussian function:

$$f_s(\text{x,y}) = \text{G(x,y)} * f(\text{x,y}) \text{ ;}$$

Where

$$\text{G(x,y)} = e^{-\frac{x^2+y^2}{2\partial^2}}$$

3.3.2. Computing the gradient magnitude and angle images:

$$\text{Edge Magnitude} = \sqrt{\text{Gx}^2+\text{Gy}^2}$$

and Edge direction = $\tan^{-1}\left(\frac{Gx}{Gy}\right)$

3.3.3. Applying non maxima suppression to the gradient magnitude image: Thus,

- Create a matrix initialized to 0 of the same size of the original gradient intensity matrix;
- Identify the edge direction based on the angle value from the angle matrix;
- Check if the pixel in the same direction has a higher intensity than the pixel that is currently processed;
- Return the image processed with the non-max suppression algorithm.

3.3.4. Detecting and linking edges using double threshholding and connectivity analysis:

- Accepting pixels as edges if the intensity gradient value exceeds an upper threshold.
- Rejecting pixels as edges if the intensity gradient value is below a lower threshold.
- If a pixel is between the two thresholds, accept it only if it is adjacent to a pixel that is above the upper threshold.

4. Experimental Results and Discussion

This section shows the results of the effect of different edge detection operators on six different images. The images were obtained from ground truth sample images [16] and were tested against Sobel, Prewitt and Canny edge detectors. For each of the images in figure 1, the first image on every row is the ground truth, the second is the result of canny edge detector on the ground truth image , the third on a row is the effect of sobel on the ground truth image and the fourth shows the effect of Prewitt on the same ground truth image for the row.

4.1. Evaluation Metrics

To effectively measure the performance of these edge detectors, Precision, Recall, and F1-Score, SSIM and FoM are utilized. These metrics are vital for making informed decisions regarding choice of edge detection operator to be adopted.

4.1.1. Precision

This is used to evaluate how accurately detected edges match the actual edges in the ground truth image.

Figure 1 Ground truth images and the effect of canny, sobel and prewitt operators

It helps determine the proportion of correctly identified edge pixels (true positives) relative to all detected edge pixels (both correct and incorrect). High Precision means that fewer false edges are detected, making the detected edges more reliable. While Low Precision implies that many false edges are included, reducing the effectiveness of the edge detector [7].

4.1.2. Precision is given as :

$$\frac{\text{TruePositives(TP)}}{\text{TruePositives(TP)+FalsePositives(FN)}}$$

Where
TP (True Positives): Pixels correctly detected as edges.
FP (False Positives): Pixels incorrectly detected as edges.

II Recall
Recall measures how well the detected edges cover the actual edges in the ground truth image. It evaluates the proportion of correctly identified edge pixels relative to all true edge pixels in the image. High Recall means that most of the true edges are detected, reducing missed edges. Low Recall Indicates that many actual edges were missed, making the detection incomplete. Recall is given as:

$$\frac{\text{TruePositives(TP)}}{\text{TruePositives(TP)+FalseNegatives(FN)}}$$

Where

TP (True Positives): Pixels correctly detected as edges.
FN (False Negatives): Actual edge pixels that

were missed by the detector.

4.1.3. F1-Score

Harmonic mean of Precision and Recall. F1-score balances precision and recall to assess the quality of detected edges. A good balance between Precision and Recall is critical to avoid over-detection or under-detection. Since edge detection involves a trade-off between detecting as many true edges as possible (recall) while minimizing false edges (precision), the F1-score strikes a balance between the two [7]. It is given as :

$$F1 = \frac{2 X \text{Precision} . \textit{Recall}}{\textit{Precision} + \textit{Recall}}$$

Note that :Precision, Recall, and F1-Score values close to 1 are desirable.

4.1.4. The Structural Similarity Index (SSIM)

The Structural Similarity Index (SSIM):is a perceptual metric that measures the similarity between two images. Unlike pixel-wise metrics such as Precision, Recall, and F1-score, SSIM evaluates the structural quality of detected edges by comparing luminance, contrast, and spatial structures [17]. It is given by:

$$\text{SSIM}=\frac{\left(2u_x u_y+\text{C}_i\right)\left(2\partial_{\text{xy}}+\text{C}_2\right)}{\left(\text{u}_x^2+\text{u}_y^2+\text{C}_1\right)\left(\partial_x^2+\partial_y^2+\text{C}_2\right)}$$

where
$\text{x}u_y$ =Mean pixel intensity of images x (detected edges) and y (ground truth edges)
$\partial_x\partial_y$= Standard deviation of x and y
∂_{xy}= Covariance between x and y, measuring structural similarity
$C_1 C_2$=Small constants to stabilize the division

SSIM ranges from -1 to 1.0; 1.0 means Perfect similarity between detected edges and ground truth. 0 indicates No Similarity while Negative values indicate structural difference.

4.1.5. Figure of Merit(FoM)

A Figure of Merit (FoM) measures how well the detected edges match the reference edges. That is, how close the detected edges are to the ideal ground truth edges [18]. Pratt's FoM is given as:

$$\text{FoM}=\frac{1}{N_d,\text{N}_r}\sum_{\text{i}=1}^{N_d}\frac{1}{1+\alpha\text{d}}\,\frac{2}{i}$$

N_d= number of detected edge pixels
N_r= number of reference edge pixels
d_i= Euclidean distance between a detected edge pixel and the closest reference edge pixel
α = scaling constant (commonly 1/9)

FoM ranges from 0 to 1. FoM of 1 implies Perfect edge detection (*detected edges perfectly align with reference edges*); while FoM of 0 shows poor detection with large deviations.

Table 1 shows the result obtained by evaluating the performance of the operators on the images using Recall, Precision, F1-score, SSIM and FoM metrics.

5. Discussion

Results show that canny operator outperforms sobel and prewitt in detecting edges. It demonstrated superior performance in Recall, F1-Score, and FoM, highlighting its ability to detect more edges consistently, albeit with slightly lower structural similarity. Sobel achieved the highest Precision and SSIM values, indicating that while it detects fewer edges, it does so very accurately and preserves image quality effectively. Prewitt maintained a balanced performance, ranking closely behind Canny in Recall and F1-Score, and near Sobel in Precision and SSIM, positioning it as a strong middle-ground choice. Overall, Canny would be preferable when maximizing edge detection is critical, whereas Sobel would be ideal where edge quality and image structure are priorities. Prewitt offers a practical compromise between detection quantity and quality.

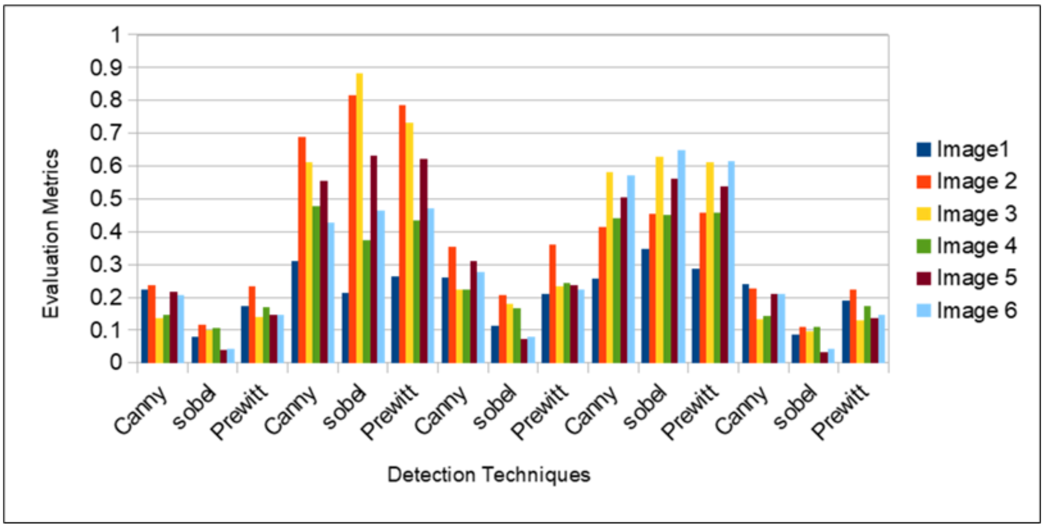

Figure 2 Performance chart

Table 1 Performance Table

Evaluation Metric	Edge Detection Technique	Image1	Image 2	Image 3	Image 4	Image 5	Image 6
Recall	*Canny*	0.2243	0.2383	0.1370	0.1453	0.2169	0.2055
	sobel	0.0783	0.1178	0.1006	0.1069	0.0378	0.0433

	Prewitt	0.1724	0.2349	0.1380	0.1698	0.1465	0.1472
Precision	*Canny*	0.3102	0.6899	0.6126	0.4775	0.5558	0.4274
	sobel	0.2118	0.8148	0.8834	0.3728	0.6317	0.4657
	Prewitt	0.2639	0.7853	0.7318	0.4326	0.6201	0.4715
F1-Score	*Canny*	0.2604	0.3542	0.2239	0.2228	0.3120	0.2776
	sobel	0.1143	0.2058	0.1807	0.1661	0.0713	0.0792
	Prewitt	0.2086	0.3616	0.2322	0.2439	0.2370	0.2243
SSIM	*Canny*	0.2586	0.4143	0.5831	0.4422	0.5058	0.5706
	sobel	0.3487	0.4529	0.6287	0.4522	0.5597	0.6478
	Prewitt	0.2861	0.4572	0.6114	0.4587	0.5377	0.6146
FoM	*Canny*	0.2411	0.2264	0.1321	0.1428	0.2088	0.2091
	sobel	0.0871	0.1101	0.0970	0.1091	0.0340	0.0422
	Prewitt	0.1891	0.2243	0.1303	0.1735	0.1354	0.1462

6. Conclusion

Edge detection techniques have been extensively explored in image processing research. In particular, the Sobel, Prewitt, and Canny operators have been fundamental in a wide range of studies, contributing to advancements in object detection, medical imaging, and computer vision. It is evident that while Sobel and Prewitt are efficient for simple, noise-free applications. Canny remains the preferred choice when precision, robustness and edge continuity are critical.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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