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Image Edge Detection Using Canny and Sobel Techniques

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KEYWORDS

Edge detection; Canny edge detection; Sobel edge detection; Image Processing; Performance Evaluation.

ABSTRACT

Finding edges is an important part of many image processing tasks, such as medical imaging, recognizing biometrics, and finding objects. But there isn't a single algorithm that works best in every case. We compared the Sobel and Canny operators on four standard grayscale benchmark images (Camera, Coins, Moon, Page) using five different metrics: runtime, edge pixel count, edge density, connected components, and average component area. Sobel was faster (8.10 ms vs. 13.28 ms) and made edges denser (8.93% vs. 6.59%). However, it also made almost twice as many connected components (469.0 vs. 217.5), which is a sign of fragmented edge maps because it is sensitive to noise. Canny always made edges that were thinner and clearer. This was especially true for the picture of the Moon (105 vs. 513 parts). Sobel is better for tasks that need speed, while Canny is better for tasks that need high accuracy, noise resistance, and edge continuity in all cases, one algorithm is not better than the other.

1. INTRODUCTION

The bottom and top of the picture are pointed by discontinuities of a sudden change. Essentially there are three image edges namely; vertical, diagonal and horizontal. These edge types fill in with the form of the image in between them. Since several tasks heavily rely on the ability to detect these edge of images, more analysis is needed in order to hone the detection tools [1,2]. The edge detection operation at the low-level in the images processing and computer-vision applications is carried out in a diverse range of applications. These applications determine and denote any sharp discontinuities an image has in order to detect the edges with precision. Such discontinuities are defined by abrupt change in the intensity of pixels and they recognize the outlines of objects in the picture. Consequently, the limits of each area in the image are defined by each edge and the limits are utilized to determine objects in the image so as to divide up the image and identify objects stored on the image [3,4].

The most common task of most computer vision algorithms, such as edge-based face recognition, target recognition and obstacle detection, and image compression is outlining the boundaries of every object. It follows, then, that edge detection is required to extract the edges of an image and that there exists a plethora of edge detection resources. All of the edge detecting operators operate by identifying the vertical, horizontal, corner and step edges in the image, the quality of the detection depends on the noise in an image, on the illumination of the image, on the density of the edges and by objects that differ in intensity with the edges of any particular object [2,5,6].

Canny edges are related to image boundaries, and as such are of crucial importance to proper edge detection in image processing. These edges are denoted by noticeable contrasts in intensity, or by a large fluctuation of intensity between two adjacent pixels. Through adequate edge detection, all the useless information is filtered out of an image and as a result, the size of an image is significantly decreased and the data under consideration is also decreased, but the significant structural properties of the image are retained. The sobel operator is one such edge detector: first, it computes the two-dimensional spatial gradient of an image, and then computes the absolute magnitude of gradient (strength of an edge) of each pixel of the image. This is performed using two 3×3 convolution filters; the first one approximating the gradient of the image over the x-axis (column) and the second one over the y-axis (row) [7–9].

This paper will provide some comparison of various techniques of image edge detection with special attention to two techniques. In Section II the findings of some significant articles in this field would be discussed. The proposed methodology for edge detection will then be highlighted in Section III. The experimental studies and discussion will then be given in Section IV. Lastly, Section V provides a conclusion about the topic, and a possible solution to edge detection is recapped in a single paragraph.

2. LITERATURE REVIEW

The past decades witnessed edge detection being a focal point in image processing research, with a vast amount of literature including classical operator-based operators, as well as application-focused adaptations. This chapter takes a survey of the most important contributions in the context of the Sobel and Canny algorithms.

2.1 Classical Edge Detection Operators

Edge detection algorithms started as early as 1963 with the work of Lawrence Roberts whose cross-differential operator was among the first attempts at using local pixel differences to detect edges [10]. Although the Roberts operator was computationally efficient, it was subject to noise to great extent and therefore inefficient in practice. This was then succeeded by Prewitt operator in 1970 which employed a 3 x3 convolution mask and which showed better results in high noise images, as well as in pixel-value fading of images [2]. Maini and Aggarwal [11], attempted to give a detailed survey of these initial approaches, compare the performance of Roberts, Prewitt and Sobel operators, and found that each algorithm has its own set of strengths and weaknesses based on the type of imaging conditions, which is exactly the question that the current paper aims to compare.

Sobel operator came about in the early 1970s and it was an extension of the Prewitt operator, which involved weighted averaging of the image and then proceeded to the differential operator. This weighting enhances its strong point over Roberts and Prewitt, yet its processing speed is still the speedy one. Ravivarma et al. [7], provided a very detailed technical description of the design of Sobel operator and real implementation on field-programmable gate arrays (FPGAs), showing that Sobel has a very low computation requirements which makes it ideal to perform real-time edge detection tasks. It was established that both Sobel 3×3 convolution masks are effective in extracting gradient information in horizontal and vertical directions to create edge maps with reasonable continuity in most situations in an image.

A significant improvement in edge-detectors came in a proposal by John Canny in 1986 [12], called the Canny edge detector. Instead of merely computing the magnitude of the gradient, Canny developed edge detection as a three-criteria optimization problem with formal criteria: good detection, good localization and single response to one edge. The algorithm does this by a series of steps which includes the following: Gaussian smoothing, gradient calculation, non-maximum suppression and the hysteresis based double threshold, which results in the use of a multi stage pipeline. A comparative study by Shrivakshan and Chandrasekar [13] established the fact that Canny is always more effective in edge continuity/noise resistant than Sobel, Prewitt, and Roberts, but at greater computational cost.

2.2 Comparative Studies of Canny and Sobel

The edge detector of Canny and Sobel have been directly compared with respect to performance evaluations over various types of images and evaluation measures. Othman, Haron, and Kadir [14] explicitly compared Canny and Sobel with the help of magnetic resonance images (MRI) and applied the two algorithms with their convolution masks. Their results showed that Canny gave out thinner, more localized edges whereas Sobel gave out thicker edges- a property due to their sensitivity to noise in images. The significance of this difference in edge thickness is that the wider the edge, the less accurate remaining processing procedures, such as segmentation and object recognition may be.

Bao, Zhang, and Wu [15] presented a larger comparative study that used objective elements of performance to compare Sobel, Prewitt, Roberts, Laplacian and Canny operators in a multicolored image using the Peak Signal-to-Noise Ratio (PSNR), Mean square errors (MSE), and Figure of Merit (FOM) metrics. Their findings were always that Canny produced the best FOM values, so it had the best detection quality, and that Sobel and Prewitt were similar, but lower quality results compared to Canny. It is important to note, however, that Sobel is also more appropriated to be used in low-noise conditions since the simplified calculations are more advantageous than the maximization of the processing speed accuracy. This accuracy/efficiency trade-off is a theme of the edge detection literature, and the contents of the debate that the current paper details.

In a more recent work, Canny and Prewitt as well as Sobel, Roberts and Laplacian of Gaussian were compared based on MSE, PSNR, Structural Similarity Index Measure (SSIM) in which the comparison was done on an albums of roads image [16]. The results indicated that the performance of algorithms was much sensitive in terms of the image domain and noise environment, thus supporting the main idea of the paper that no general edge detecting algorithm is optimal one. The Canny algorithm produced the highest-correlated and complete edge maps in the high-detailed images and the more intuitive operators such as Roberts, were more accurate in the localization in the low-detailed cases. Table 1 overviews the main features of the most popular classical edge detectors:

Table 1. Characteristics of widely used classical edge detection operators

Algorithm	Type	Noise Sensitivity	Edge Continuity	Speed	Best Use Case
Roberts	First-order	Very High	Poor	Very Fast	Low-noise images
Prewitt	First-order	Moderate	Moderate	Fast	General use, high noise
Sobel	First-order	Moderate	Moderate–Good	Fast	Real-time processing
Laplacian (LoG)	Second-order	High	Good	Moderate	Noise-free images
Canny	Optimal	Low	Excellent	Slower	High-accuracy applications

2.3 Applications in Medical Imaging

Finding applications of edge detection algorithms in medical imaging is one of the most dynamic and significant subtopics in medical imaging research. Proper edge detection is paramount to image segmentation, which then facilitate identification and measurement of anatomical objects like tumors, lesions and organ boundaries. Another study conducted by Hou et al. [17] suggested a better Canny algorithm to identify weak edges in the image of the COVID-19 CT scan with image histogram equalization and mathematical morphology with Otsu thresholding method by combining them. The enhanced algorithm was able to deliver better values of MSE and SNR relative to the traditional implementation of Canny, which illustrates that the traditional Canny detector should be adapted to the perilous medical imaging environments marked by distorted pixel grayscale and solitary noise.

Detailed comparative evaluation of five edge detectors Canny, Sobel, etc., on medical images of three datasets: retinal images, brain tumor images, and CT lung scan images was performed [18]. The experiment has used three objective metrics (F1-score, Figure of Merit, and Precision-Recall) on low, medium and high detail images. The results indicated that the Canny operator caused the least number of results when the images were high detail with Roberts and Sobel having a similar performance when the images were of lower detail. This observation indicates the significance of aligning the edge identifying strategy with the depth and intricacy of the particular medical picture undergo processing.

Li et al. [19] also applied the Canny algorithm in the area of MRI-based diagnosis by using the algorithms to identify the edge features of MRI images of the wrist joint of a mouse patient with wrist joint injuries. Using a combination of Canny based extraction and an edge with a particle swarm optimization-support vector machine (PSO-SVM) classifier, the research obtained better diagnostic accuracy than the traditional methods. The findings demonstrated that Canny is useful in identifying the local edges of the MRI images but the authors observed that it was challenging to obtain accurate regions of interest in the complicated anatomy. These observations are in line with the rest of the literature which points out that the multi-stage pipeline of Canny results in a more favorable behavior in comparison to Sobel because it is more suitable in applications where the edge needs to be localized at stages.

2.4 Applications in Biometric Recognition

Edge detection is a fundamental component in biometric recognition systems especially in analysing face and fingerprint. In fingerprint recognition, precise edge detection plays a crucial role in increasing the ridge patterns, mining of minutiae features and the level of matching. An experiment on fingerprint recognition with edge detector and dimensionality reduction methods pitted Sobel, Prewitt, Roberts and Canny operators and discovered that post-processing or pre-processing fingerprint images with Canny commitment operator merged with Principal Component Analysis (PCA) raised recognitions rates between 88 and 64.3 percent [20]. Sobel-based preprocessing, in its turn, converted large ridges into grayscale gradients that were easier to classify with a slight reduction of the accuracy as compared to Canny.

Sobel operator has also found application in biometric applications other than fingerprints. Al-Nima et al. [21] introduced Multi-scale Sobel Angles Local Binary Pattern (MSALBP) method of extracting features to verify a person (using finger texture biometrics). The proposed method used Sobel operator at various scales to get information about the vertical and horizontal edge angle information and obtained a recognition rate of 99.32 percent on the FV-USM finger vein database. This application shows that though Sobel can be a inferior method than Canny when used as a general edge detector, its gradient results can make very effective inputs to special feature extraction pipelines in biometrics.

2.5 Limitations and the Need for Further Research

Although much research has been conducted over the years the edge detection literature has continually indicated the fact that none of the algorithms can be as certain to meet all imaging requirements as one. A review of edge detecting methods by Poobathy and Chezian [22] compared Sobel, Canny, Prewitt, Roberts and Laplacian of Gaussian and found that Canny algorithm is more computationally expensive than the others and hence is less applicable to real time applications on limited resource based hardware. The Sobel operator is slower, but produces thicker edges and is more sensitive to noise, so reducing the accuracy in situations where such precision is needed, such as segmentation. The survey concluded that the specific application area requirements like tolerable noise level, processing speed, and level of edge continuity of the application should inform the type of algorithm to use.

More current literature has focused on the hybrid and optimizing strategies to overcome individual limitations of classical operators. Improvements to the performance of Canny on noisy CT imaging were made by Hou et al. [17], which combine the histogram equalization algorithm with the Otsu algorithm, and Ravivarma et al. [7] demonstrated that the software cost was nearly 80 times, when the Sobel operator is implemented at hardware level on FPGAs. These advances imply that the study of edge detection in future will be directed more towards domain specific optimization and hardware acceleration as opposed to trying to reconcile a generally best algorithm. This finding agrees with and supports the main idea of the current paper that either Canny or Sobel still have unique benefits depending on the context of application and more in-depth studies should be conducted to implement more powerful and flexible solutions.

3. METHODOLOGY

The both Sobel and Canny edge detectors were tested on four grayscale benchmark images of common objects, namely, Camera, Coins, Moon and Page (as seen in Figure 1). These images have been carefully chosen to have a variety of structural complexity, density of edges and noise properties. Table 2 is a summary of the main characteristics and justification of each image chosen.

Table 2. properties and rationale for the selected images

Image	Resolution	Key Characteristics	justification for Selection
Camera	272 × 272	Complex scene, moderate noise, mixed edge types	Representative of general-purpose natural scenes
Coins	246 × 300	Circular edges, uniform background, low noise	Tests detection of curved and smooth boundaries
Moon	537 × 358	Low contrast, textured surface, significant noise	Evaluates noise robustness and weak edge detection
Page	2200 × 2800	High-density text edges, strong contrast	Assesses performance on fine, closely spaced edges

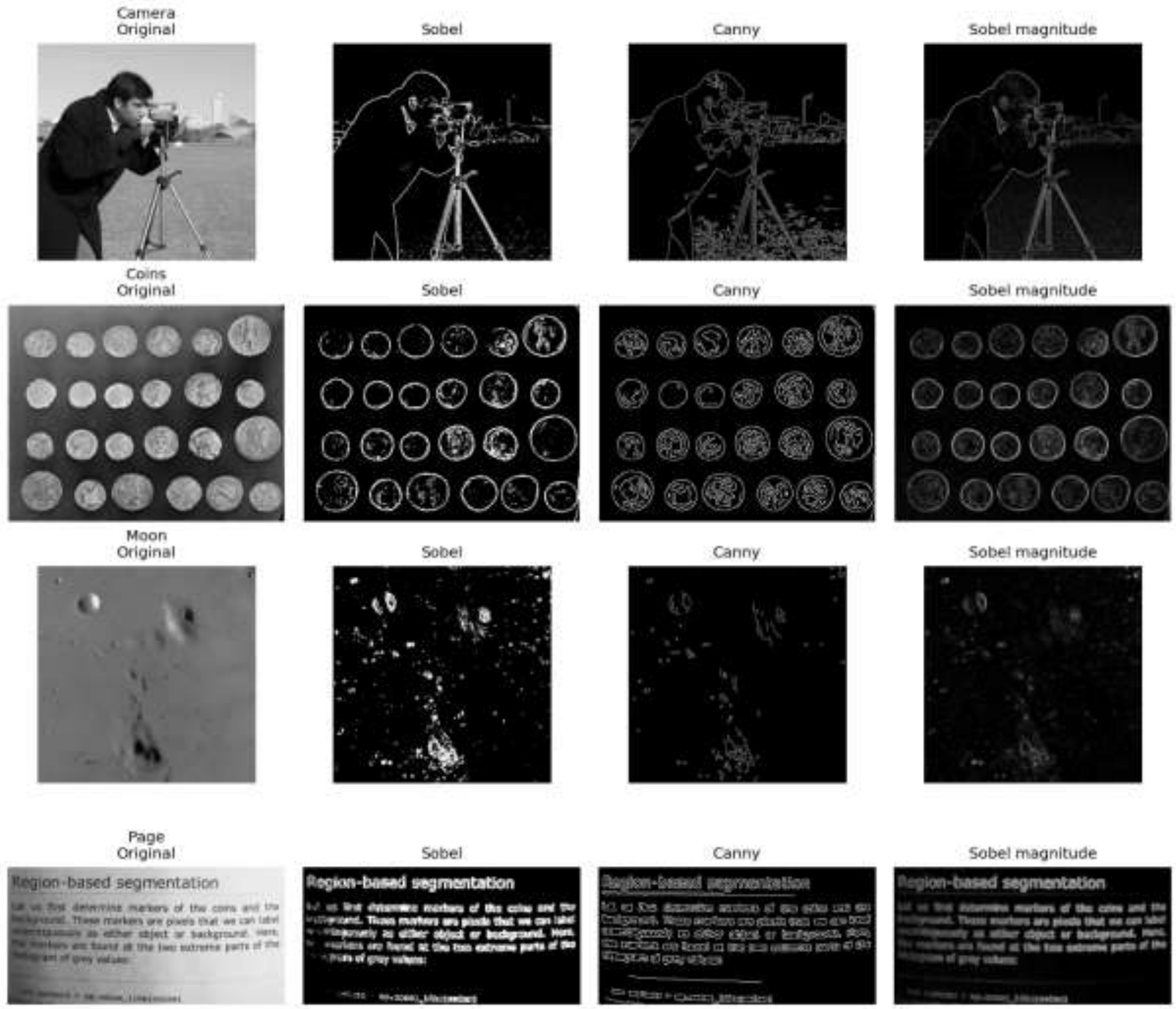

Fig.1. Comparison of the original images with Sobel output, Canny output and Sobel gradient magnitude

The two algorithms were executed in python with the OpenCV and scikit-image encoder, which offers standardized well-verified executions of the two operators. All the pictures were made to grayscale before processing. Algorithms used were applied to the four test images using the same state of computation in order to provide a fair comparison.

With the Sobel detector, 3x3 convolution masks were employed to calculate the horizontal or the vertical gradient elements, and to calculate the magnitude of the gradient the Euclidean norm of the two elements. The gradient magnitude map was next subjected to Otsu method to come up with a binary edge image which gives an automatic and repeatable threshold selection.

The Canny detector was set up with the following settings: Gaussian smoothing standard deviation $\sigma = 1.4$, low hysteresis threshold = 0.08, and high hysteresis threshold = 0.20. The consensus among the majority is these values are the default settings that are effective on various types of images since they strike a reasonable balance between noise suppressions and edge sensitivity.

To be able to objectively and multidimensionally compare performance, five quantitative measures were taken in each image-algorithm combination. Each metric, as well as its interpretation, is defined in Table 3.

Table 3. Measures of edge detection performance

Metric	Description	Interpretation
Runtime (ms)	Total processing time in milliseconds	Lower values indicate faster computation

Edge Pixels	Total number of pixels classified as edges	Higher values indicate denser edge detection
Edge Density (%)	Edge pixels as a percentage of total image pixels	Reflects the proportion of the image identified as edges
Connected Components	Number of discrete edge segments in the binary map	Fewer components indicate more continuous, coherent edges
Avg. Component Area	Mean pixel area of each connected edge segment	Larger values indicate longer, less fragmented edge structures

A. Sobel Operator

The Sobel operator estimates image gradients in the horizontal and vertical directions using two convolution kernels:

$$G_x = \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix}$$

$$G_y = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ +1 & +2 & +1 \end{bmatrix}$$

The gradient magnitude is computed as:

$$G = \sqrt{G_x^2 + G_y^2}$$

where:

- $G_x$represents the horizontal gradient,
- $G_y$represents the vertical gradient,
- Grepresents the edge strength.

The Sobel operator enhances edge information while partially smoothing image noise due to the weighted convolution masks.

B. Canny Edge Detector

The Canny detector performs edge extraction through a multi-stage process:

1. Gaussian smoothing for noise reduction:

$$G(x, y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

Gradient computation using derivative filters.

2. Non-maximum suppression to obtain thin edges.
3. Double-threshold hysteresis to preserve strong edges while suppressing weak noisy responses.

The Canny algorithm is designed to satisfy three optimality criteria:

- Good edge detection,
- Accurate edge localization,
- Minimal multiple responses to a single edge.

4. EXPERIMENTAL RESULTS AND DISCUSSION

A. Quantitative Results

Table 4 indicates the values that were measured in each pair of image and method. Table 5 indicates the mean of the four test images.

Table 4. Per-image quantitative results for Sobel and Canny edge detectors

Image	Method	Runtime (ms)	Edge Pixels	Edge Density (%)	Components	Avg Component Area
Camera	Sobel	14.94	14,413	5.50	748	19.27
Camera	Canny	20.04	15,298	5.84	324	47.22
Coins	Sobel	4.82	10,039	8.63	444	22.61
Coins	Canny	8.80	9,850	8.47	216	45.60
Moon	Sobel	8.75	11,323	4.32	513	22.07
Moon	Canny	18.14	2,694	1.03	105	25.66
Page	Sobel	3.88	12,670	17.27	171	74.09
Page	Canny	6.13	8,085	11.02	225	35.93

Table 5. Mean values across all four test images

Method	Runtime (ms)	Edge Pixels	Edge Density (%)	Components	Avg Component Area
Sobel	8.10	12,111	8.93	469.0	34.51
Canny	13.28	8,982	6.59	217.5	38.60

B. Discussion of Findings

The experimental findings can support the tendencies revealed in the literature and confirm the main thesis of the paper that Sobel and Canny have various benefits based on the situation that they are used.

Sobel had an average of time of 8.10 ms as compared to Canny which was 13.28 ms. This outcome is not surprising since Canny multi-step pipeline, which involves the application of the Gaussian smoothing, non-maximum suppression and hysteresis thresholding, involves more calculations than Sobel, which simply computes the time gradients directly.

Sobel had more edge pixels on average (12,111 vs. 8,982) and a higher edge density (8.93% vs. 6.59%). This compares to the results of Othman et al. [12] and Bao et al. [13]: Sobel is prone to generating fat responses on edges due to its sensitivity to changes in intensity and absence of non-maximum suppression. This may be useful in situations where edge completeness is a more significant aspect than any other, but may cause things to become less precise when accurate localization of thin boundary boundary requirements are required.

Edge coherence: Canny made a lot fewer connected components on average (217.5 vs. 469.0), which means that the edge structures were cleaner and more coherent. The number of parts with rather large overlap areas implies that the edges are more interconnected and not so discontinuous. It is a significant attribute towards the subsequent stages, which are object segmentation and recognition. The difference is the greatest on the Moon picture: Sobel created 513 parts whereas Canny created 105. Sobel discovered a greater number of edge pixels about four times over, though.

The over-segmentation: Sobel has more component-wise in certain images, such as Camera and Coins, which make it appear that the images had too many segments. Sobel aims at detecting faux edges brought about by noise which cannot be removed without hysteresis thresholding. This is consistent with qualitative result that Sobel results exhibit less continuity in detected edges than the Canny results.

These findings confirm the argument that Sobel performs better on speed, whereas Canny is better in situations where continuity of edges is the main issue and edges can also withstand noise but also properly localize the edges.

5. CONCLUSION

This paper has made a comparison between Sobel and Canny edge detection approaches based on four standard grayscale benchmarked images both qualitatively and quantitatively. The experiments indicate that there is no single algorithm that can be universally superior to all the image processing situations. The ability of Sobel to work in real-time and not consume a lot of memory makes sobel good in real-time applications. It however creates edge maps that are viscous and more fragmented and in addition, it is sensitive to noise. Although more expensive to compute, the edges Canny does are cleaner and smoother. This renders it the most suitable with regards to medical imaging and biometric recognition which ought to be highly precise and not to pick noise.

The resolution, level of noise and structural complexity of the image, with regard to the technology employed to process it, is also determinant of the quality of edge detection. In this instance the practitioner must choose the most appropriate way depending on the requirements of the application. Future studies should then focus on exploring hybrid approaches and hardware-implemented (including FPGA-based Sobel processing and optimized Canny pipelines) approaches that can address the performance gap between speed and accuracy. There is room for future research on hybrid edge detection methods that could take advantage of the efficiency of Sobel and the structure of Canny. Also, future work can include the use of adaptive thresholding, deep learning edge extraction models, GPU acceleration, and FPGA implementation for real-time applications on high speed. A wider range of datasets, including color images, medical data, and satellite and video streams, could also give a more complete picture of how algorithms behave in the real world.

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الكشف عن حواف الصور باستخدام تقنيات Canny and Sobel

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الملخص

يُعدّ تحديد الحواف جزءًا أساسيًا من العديد من مهام معالجة الصور، مثل التصوير الطبي، والتعرف على البيانات البيومترية، وتحديد الأجسام. ولكن لا توجد خوارزمية واحدة تُناسب جميع الحالات. قارنّا بين مُعاملي سوبل وكاني على أربع صور قياسية رمادية (الكاميرا، العملات المعدنية، القمر، الصفحة) باستخدام خمسة معايير مختلفة: زمن التشغيل، وعدد بكسلات الحواف، وكثافة الحواف، والمكونات المتصلة، ومتوسط مساحة المكون. كان سوبل أسرع (8.10 مللي ثانية مقابل 13.28 مللي ثانية) وجعل الحواف أكثر كثافة (8.93% مقابل 6.59%). مع ذلك، فقد أنتج أيضًا ما يقرب من ضعف عدد المكونات المتصلة (469.0 مقابل 217.5)، وهو ما يُشير إلى تجزئة خرائط الحواف نظرًا لحساسيته للتشويش. أما كاني، فقد أنتج دائمًا حوافًا أرق وأكثر وضوحًا، لا سيما في صورة القمر (105 مقابل 513 جزءًا). تُعد خوارزمية سوبل أفضل للمهام التي تتطلب سرعة، بينما تُعد خوارزمية كاني أفضل للمهام التي تتطلب دقة عالية ومقاومة للضوضاء واستمرارية الحواف. في جميع الحالات، لا توجد خوارزمية أفضل من الأخرى.

الكلمات المفتاحية

كشف الحواف؛ كشف الحواف باستخدام خوارزمية كاني؛ كشف الحواف باستخدام خوارزمية سوبل؛ معالجة الصور؛ تقييم الأداء.