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Improved Edge Detection Algorithms For Digital Image Processing: A Practical-Oriented Study

Dang Gia Dung, Nguyen Thuy May, Nguyen Thanh Phong,
Ngo Thi Anh Hang, Tran Minh Hai
Faculty Of Technology And Engineering, Thai Binh University, Hung Yen, Viet Nam

Abstract
Edge detection is a crucial stage in digital image processing, directly affecting the effectiveness of image segmentation and object recognition. However, traditional algorithms such as Sobel, Prewitt, Roberts, and Canny still exhibit limitations when dealing with noisy images, low-contrast conditions, or real-time processing requirements. This paper investigates and proposes several improvements to common edge detection algorithms through parameter adjustment, enhanced preprocessing, and adaptive threshold selection based on image characteristics. Experimental results on various image datasets demonstrate that the proposed methods improve detection accuracy, reduce noise, and enhance edge continuity compared with conventional approaches.
Keywords: *Edge detection; Digital image processing; Algorithm improvement; Feature extraction.*

I. Introduction

In the context of digital transformation and higher education reform, digital image processing has increasingly played a vital role in intelligent systems, scientific research, and education. Among these techniques, edge detection is a fundamental approach for identifying object boundaries, directly influencing the effectiveness of image segmentation, object recognition, and computer vision tasks [1–4]. This technique has been widely applied in medicine, security and surveillance, Industry 4.0, and digital education, where high accuracy and robustness are required under complex imaging conditions [5–9]. However, traditional edge detection algorithms such as Sobel, Laplacian, and Canny still exhibit limitations when dealing with noisy images and varying illumination conditions [10, 11]. Therefore, this study focuses on the analysis and quantitative evaluation of classical edge detection methods on multi-domain datasets using OpenCV, employing PSNR, SSIM, and EPC metrics, and proposes application-oriented directions for teaching, research, and automated assessment systems in digital education.

II. Related Work

This study applies the OpenCV library and the Python programming language to implement edge detection algorithms and designs a standardized experimental workflow that can be reused in teaching courses such as *Digital Image Processing* or *Computer Vision*. The proposed workflow consists of data normalization, image preprocessing, algorithm implementation, and qualitative as well as quantitative evaluation. The datasets are selected from multiple domains, including healthcare, transportation, environmental monitoring, and industry, to ensure data diversity and broad reproducibility of the experimental results.

Sobel Method

The Sobel method is a gradient-based edge detection technique used to identify edge pixels in an image. This method employs two 3×3 convolution kernels to approximate the partial derivatives in the horizontal (Gx) and vertical (Gy) directions [8].

$$G_x = \begin{vmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{vmatrix}, G_y = \begin{vmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ +1 & +2 & +1 \end{vmatrix} \quad (1)$$

The Sobel operator is based on the concept of gradient computation, where the image gradient measures the rate of change of the image intensity function. This operator performs convolution between the kernel and the input image to compute the gradient magnitude and direction at each pixel. In terms of computational performance, the Sobel operator has a complexity of O(n2)O(n^2)O(n2), where nnn denotes the image size, and it can be designed to operate with a two-phase 10-MHz clock, performing approximately 200×106200 \times 10^6200×106 additions per second to produce magnitude and direction outputs in each clock cycle. Although effective in detecting high-contrast edges and relatively robust to mild noise, the Sobel operator exhibits significant limitations when processing complex images due to the limited edge resolution of the 3×3 kernel and its sensitivity to moderate noise levels [1]. This method is suitable for basic image processing applications or as a preprocessing step in more advanced edge detection systems; however, it requires integration with noise filtering techniques or threshold tuning to achieve optimal performance on real-world data [17].

Laplacian Method

The Laplacian operator is a second-derivative operator commonly used in edge detection and can provide better edge localization than first-derivative-based edge detectors. This method focuses on the curvature of intensity values and employs the Laplace operator to detect edges based on the second-order derivative.

$$\nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} \quad (2)$$

The Laplacian operator is a second-derivative-based edge detection method that is capable of detecting isotropic edges, independent of the gradient direction. Its main advantages include rotational symmetry and accurate edge localization through the identification of zero-crossing points in the signal. However, due to the inherent nature of second-order derivatives, this method exhibits high sensitivity to noise, which leads to noise amplification and the generation of spurious edges [18]. To overcome this limitation, the Laplacian operator is commonly combined with a Gaussian filter to form the Laplacian of Gaussian (LoG), which reduces noise while preserving effective edge detection capability. The LoG method has been demonstrated to be one of the most stable and accurate edge detection techniques in image processing [19].

Canny Method

The Canny algorithm, proposed by John F. Canny in 1986 [4], is one of the most effective edge detection methods in digital image processing. It was designed based on three criteria: high detection accuracy, good localization, and a single response to each edge. The algorithm consists of four main steps: (i) smoothing the image using a Gaussian filter to suppress noise; (ii) computing the gradient magnitude and direction; (iii) non-maximum suppression to thin the edges; and (iv) hysteresis thresholding using two thresholds to connect true edges and eliminate false ones. This algorithm produces thin, accurate, and stable edges, and is particularly effective in noisy environments due to the integration of Gaussian filtering [20]. However, its relatively high computational cost and sensitivity to threshold parameters are notable limitations [21]. In the medical field, the Canny algorithm is still widely applied and is often integrated with deep learning techniques to enhance performance, especially in X-ray and MRI image analysis [22]. Owing to its accuracy and reliability, the algorithm remains a fundamental approach in biomedical edge detection.

III. Theoretical Background And Proposed Method

Edge detection is defined as the process of identifying points in an image where the light intensity changes abruptly, which are typically represented by points with maximum gradients (first-order derivatives) or zero-crossings of second-order derivatives [13]. For a two-dimensional (2D) image f(x,y)f(x, y)f(x,y), edges can be detected by computing the gradient vector:

$$\nabla f(x, y) = \left[\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}\right] \quad (3)$$

The gradient magnitude is defined as:

$$|\nabla f(x, y)| = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2} \quad (4)$$

Or it can be approximated using the following formula to reduce computational complexity:

$$|\nabla f| \approx \left|\frac{\partial f}{\partial x}\right| + \left|\frac{\partial f}{\partial y}\right| \quad (5)$$

A large gradient value indicates a high likelihood that the corresponding pixel lies on an edge, with the threshold typically determined through empirical analysis or statistical methods [14]. For second-derivative-based approaches, the Laplacian operator is a commonly used second-derivative operator in edge detection and can provide better edge localization than first-derivative-based edge detectors such as the Sobel operator [15]. Operators such as Sobel, Laplacian, and Canny employ convolution with characteristic kernels to approximate derivatives, thereby enabling effective edge detection through digital signal processing techniques [16].

IV. Results And Discussion

The study applied three widely used edge detection algorithms—Sobel, Laplacian, and Canny—to a set of real-world images from various domains, including medical imaging, transportation, natural environments, and industrial quality inspection. The experiments were conducted using Python 3.8 with OpenCV 4.5.2 on a computing platform equipped with an Intel Core i7-10700K processor and 16 GB of RAM. The experimental procedure followed a standardized workflow comprising: conversion of images to grayscale; image smoothing using a Gaussian filter (applied to Laplacian and Canny); application of edge detection operators with optimized parameters; and evaluation of the results from both qualitative and quantitative perspectives based on three criteria: edge sharpness, edge thinness, and noise suppression capability.

The experimental results indicate that each edge detection algorithm exhibits distinct characteristics and performance when applied to different types of real-world images, as illustrated in Fig. 1. The Sobel method demonstrates fast and clear edge detection with an average processing time of 15–25 ms for 512×512-pixel images; however, it often produces jagged edges and noise when the input images are not preprocessed, particularly in low-contrast images, as shown in Fig. 1b. In contrast, the Laplacian method generates sharper and thinner edges (edge thickness ≈ 1 pixel) but is prone to producing false edges, especially in regions with fine details or complex textures, due to its high sensitivity to salt-and-pepper and Gaussian noise, as illustrated in Fig. 1c. Conversely, the Canny algorithm delivers superior performance with thin (sub-pixel accuracy), clear, and low-noise edges, and is particularly effective for low-contrast images such as medical images (CT, MRI) with SNR < 15 dB or industrial images captured under uneven illumination conditions, as shown in Fig. 1d. Nevertheless, the Canny algorithm requires longer processing times (45–80 ms) and careful fine-tuning of threshold parameters for different image types.

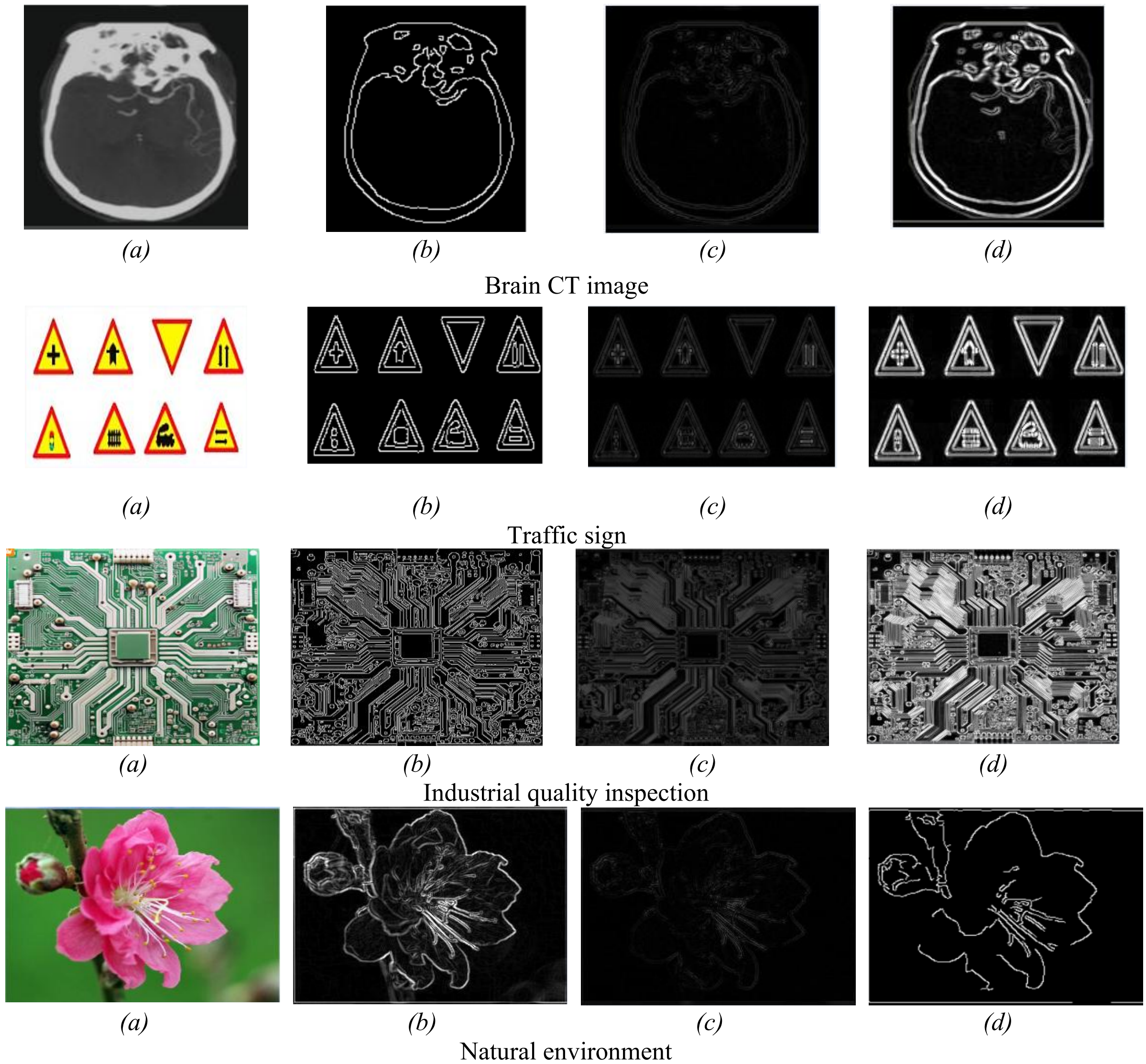

Figure 1. Image results obtained by different methods: (a) Original image; (b) Sobel; (c) Laplacian; and (d) Canny.

From a quantitative perspective, this study employs three standard metrics widely used in image quality assessment: PSNR (Peak Signal-to-Noise Ratio), SSIM (Structural Similarity Index), and EPC (Edge Pixel Count) to evaluate the effectiveness of each method, as summarized in Table 1. Among the evaluated approaches, the Canny algorithm achieves the highest PSNR (27.1 dB) and the largest SSIM value (0.81), indicating a significantly better ability to preserve structural information and the quality of the original image compared to the other methods. This result is consistent with the principle of SSIM, which focuses on measuring structural distortion, whereas PSNR only estimates absolute error.

The Sobel method yields a moderate PSNR value (23.5 dB) but detects a relatively large number of edge pixels (>12,340 pixels), which may lead to over-segmentation and increased noise in the output image, particularly for images with complex textures. The Laplacian method records the highest edge pixel count (14,912 pixels); however, it exhibits the lowest PSNR and SSIM values, reflecting the generation of spurious edges and a degradation in the structural quality of the original image.

Based on these results, it can be concluded that the Canny algorithm is the optimal choice for applications requiring accurate edge detection and effective noise suppression, making it particularly suitable for medical image processing and computer vision engineering applications.

Table 1. Performance comparison of edge detection methods

METHOD	PSNR (dB)	SSIM	PIXELS
Sobel	23,5	0,65	12,340
Laplacian	21,8	0,58	14,912
Canny	27,1	0,81	10,874

In addition to traditional methods, this study further investigates the modern **Holistically-Nested Edge Detection (HED)** model, a deep learning–based approach built upon a multi-layer CNN architecture. Compared to the Canny algorithm, HED produces thinner, more continuous, and more accurate edges, and is particularly effective in image regions with blurred transitions or high noise levels. Its ability to learn contextual features makes HED well suited for medical images and specialized applications. However, HED requires large training datasets, substantial computational resources, and is difficult to deploy on real-time systems or embedded devices.

Overall, the analysis indicates that no single edge detection algorithm is optimal for all scenarios. Methods such as Sobel are suitable for simple images and applications requiring fast processing; Laplacian is effective for images containing fine details; Canny provides thin, low-noise edges and is appropriate for applications demanding high accuracy; whereas deep learning–based models such as HED, DexiNed, or RCF are better suited for complex images that require deep contextual analysis.

The effectiveness of edge detection is strongly influenced by preprocessing steps, noise filtering techniques, and, in particular, algorithm parameters (e.g., threshold values in Canny and the sigma parameter in Gaussian filtering). Selecting appropriate algorithms and parameter settings is therefore a critical factor in optimizing image processing performance.

V. Conclusion

Edge detection is a fundamental step in digital image processing and plays a crucial role in applications such as image segmentation, object recognition, medical imaging, intelligent transportation, and computer vision. Through experiments with multiple algorithms, this study demonstrates that traditional methods such as Sobel, Laplacian, and Canny each exhibit specific advantages depending on image characteristics and application objectives. In particular, Sobel is simple and fast, making it suitable for real-time systems but with limited accuracy; Laplacian is sensitive to fine details but prone to noise if preprocessing is inadequate. The Canny algorithm produces sharp, thin, and stable edges and is therefore the optimal choice among classical methods.

On the other hand, modern techniques such as HED, RCF, and DexiNed, which employ deep neural networks, achieve higher accuracy due to their strong ability to learn spatial and contextual features. However, high computational costs and dependence on large training datasets remain significant challenges. Overall, no single algorithm is universally optimal; the selection should be based on task requirements, data characteristics, and system processing capabilities.

Despite significant progress, edge detection still offers substantial potential for further research and development. Promising directions include the integration of traditional and deep learning approaches, such as developing hybrid models that combine the speed and simplicity of Canny with the contextual learning capabilities of HED or DexiNed to enhance performance in complex environments; optimizing algorithms for embedded devices by designing lightweight deep learning models suitable for deployment on mobile devices, IoT platforms, or smart cameras to support real-time systems; and advancing adaptive and unsupervised learning methods, including self-supervised or unsupervised models, to improve edge detection robustness under varying illumination, high noise levels, or limited labeled data.

In addition, further expansion into specialized application domains is warranted, including medical imaging (tissue segmentation, tumor boundary detection, vascular and neural structure analysis), intelligent transportation (lane detection, obstacle and traffic sign recognition), industrial robotics (supporting precise manipulation through object boundary recognition), and security and defense (processing satellite and infrared images for surveillance purposes). Moreover, standardizing performance evaluation metrics by incorporating perceptual metrics tailored to specific application contexts, alongside PSNR, SSIM, and edge pixel count, represents another important research direction.

In summary, edge detection is no longer merely a preprocessing step but is increasingly becoming an essential component of the computer vision pipeline and digital education. A balanced integration of traditional algorithms and deep learning techniques will foster sustainable and effective development, meeting technical requirements while enhancing the quality of teaching and research in the context of digital transformation in higher education. The results of this study not only contribute academic value to the field of digital image processing but also hold strong potential for practical applications in intelligent education systems, virtual laboratories, and online learning platforms. The integration of classical algorithms with deep learning models opens up interdisciplinary research directions that address technical demands while promoting innovation in teaching methodologies and assessment in the era of digital transformation in higher education.

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