Quantum Inspired Edge Detection for Real-Time Surveilliance Systems

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***Abstract*— Edge detection plays an important role in surveillance systems for identifying the object boundaries in video streams. This paper presents a quantum-inspired edge detection approach based on frequency domain processing using Fast Fourier Transform (FFT). The method applies spectral filtering followed by inverse transformation and Laplacian refinement to extract the edges from the video frames. The proposed system is implemented in a real-time processing pipeline and compared with the classical edge detection methods such as Sobel and Canny. Experimental testing shows that the proposed approach operates in real time while producing edge representation compared to conventional techniques. These results indicate that frequency domain processing is a practical method for surveillance-based edge detection.**

Keywords—Edge detection, Fast Fourier Transform, real-time processing, surveillance systems, frequency-domain filtering, quantum-inspired computing

I. INTRODUCTION

Edge detection is a fundamental operation in computer vision and surveillance systems for identifying object boundaries and structural information from visual data. Accurate edge extraction is essential for applications such as motion detection, object recognition, and scene analysis. Traditional edge detection techniques including Sobel and Canny are widely used due to their simplicity and efficiency; however, they often struggle under noisy conditions or illumination variations commonly observed in surveillance environments.

To address these limitations, this work proposes a quantum-inspired edge detection approach based on frequency-domain processing. The method applies Fast Fourier Transform (FFT)-based frequency-domain filtering followed by inverse transformation and Laplacian refinement to obtain edge maps. This approach enables efficient real-time processing while preserving important structural features in video frames.

The main contributions of this work are summarised as follows:

1) A frequency-domain edge detection framework inspired by quantum-style transformations.

2) A real-time implementation suitable for surveillance applications.

3) Performance comparison with classical edge detection methods.

The remainder of this paper is organized as follows. Section II describes the related work, Section III presents the methodology and experimental evaluation, Section IV discusses results, and Section V concludes the paper.

II. RELATED WORK

Edge detection has been extensively studied in image processing and computer vision due to its importance in extracting structural information from visual data. Classical gradient-based operators such as Sobel and Canny remain widely used because of their simplicity and computational efficiency; however, their performance can degrade in the presence of noise, illumination variations, or low-contrast conditions [1]–[3]. These limitations have motivated the development of alternative approaches that can provide improved robustness while maintaining real-time performance.

Frequency-domain techniques have been explored as an effective alternative for image enhancement and edge extraction. Transform-based methods utilize spectral representations to emphasize high-frequency components associated with edges and structural boundaries, enabling efficient processing and improved noise tolerance [4], [5]. Such approaches are particularly suitable for applications requiring fast computation and stable edge detection under varying environmental conditions.

Recent studies have also investigated quantum-inspired image processing techniques that emulate mathematical properties of quantum transformations using classical computation. Pon Gloria et al. proposed a transform-based framework for improving performance in video processing using quantum computation concepts [6]. Their work demonstrated the potential of transform-domain processing for enhancing computational efficiency in visual analysis tasks. However, many existing approaches focus primarily on theoretical or simulated environments. In contrast, the method proposed in this paper implements a practical real-time edge detection pipeline on live video frames using frequency-domain filtering combined with classical refinement techniques.

However, existing approaches either suffer from high computational cost or lack robustness in real-time surveillance scenarios, motivating the proposed framework.

III. METHODOLOGY

The proposed system presents a real-time edge detection framework designed for surveillance applications using a quantum-inspired frequency-domain processing approach. Instead of relying on actual quantum hardware, the method simulates quantum principles mathematically using classical computation. The system combines Fourier-based spectral filtering with classical edge detection operators to enhance edge clarity while maintaining computational efficiency.

A. Preprocessing

The preprocessing stage is mathematically defined as follows. Each input frame I(x,y) is converted to grayscale and smoothed using a Gaussian filter:

$$G(x,y) = I(x,y) * exp(-(x^2 + y^2) / 2\sigma^2) \quad (1)$$

where σ controls smoothing strength. Contrast enhancement is then applied using adaptive histogram equalization to improve structural visibility.

B. Frequency-Domain Transformation

The preprocessed frame is transformed into frequency space using a 2D Fourier Transform:

$$F(u,v) = \Sigma\, \Sigma\, f(x,y)\, e\hat{}(-j2\pi(ux/M + vy/N)) \quad (2)$$

High-frequency components represent rapid intensity changes corresponding to edges. A high-pass filter H(u,v) is applied:

$$F'(u,v) = F(u,v) \cdot H(u,v) \quad (3)$$

C. Inverse Reconstruction

The filtered signal is converted back into spatial form using inverse transform:

$$f'(x,y) = (1/MN)\, \Sigma\, \Sigma\, F'(u,v)\, e\hat{}(j2\pi(ux/M + vy/N)) \quad (4)$$

This reconstruction enhances edge regions while suppressing smooth background areas.

D. Edge Extraction

A Laplacian operator is applied to emphasize fine details:

$$\nabla^2 f = \partial^2 f/\partial x^2 + \partial^2 f/\partial y^2 \quad (5)$$

Edges are then extracted using thresholding to obtain a binary edge map.

E. Baseline Comparison

For evaluation, classical operators are also implemented. Sobel gradient magnitude is computed as:

$$G = \sqrt{}(Gx^2 + Gy^2) \quad (6)$$

and Canny detection performs gradient estimation, suppression, and thresholding. These serve as reference methods.

F. Performance Metrics

Real-time performance is measured using frame rate:

FPS = number of processed frames / time

Edge quality is evaluated using Peak Signal-to-Noise Ratio:

$$PSNR = 20 \log10(MAXI / \sqrt{}MSE) \quad (7)$$

where MAXI is maximum intensity value and MSE is mean squared error.

G. Implementation

The system is implemented using Python with OpenCV for video handling and NumPy for numerical computation. The pipeline processes frames sequentially, enabling practical real-time surveillance analysis without requiring quantum hardware.

IV. RESULTS AND DISCUSSION

A. Experimental Setup

The proposed quantum-inspired edge detection system was evaluated using real-time video streams captured from a webcam. Each frame was processed independently and resized for computational efficiency. The implementation was developed in Python using OpenCV and NumPy libraries and executed on a standard desktop environment without specialized hardware acceleration.

To validate performance, the proposed method was compared with two classical edge detection techniques: Sobel and Canny operators. These methods were selected because they are widely used benchmarks in image processing and real-time surveillance applications.

B. Performance Metrics

System performance was evaluated using computational metrics suitable for real-time video processing. The primary metric used was frame rate (FPS), defined as:

$$FPS = Number\ of\ processed\ frames\ /\ Time$$

Higher FPS values indicate better real-time capability.

In addition, Peak Signal-to-Noise Ratio (PSNR) was used as a secondary metric to measure overall similarity between processed frames and original frames. PSNR is computed as:

$$PSNR = 20\, log10(MAX / \sqrt{MSE})$$

where MAX is the maximum pixel intensity and MSE represents mean squared error. Although PSNR is traditionally used for reconstruction tasks, it provides a general indication of structural preservation.

C. Quantitative Results

The experimental results show measurable performance differences between the evaluated methods as illustrated in Fig. 1.

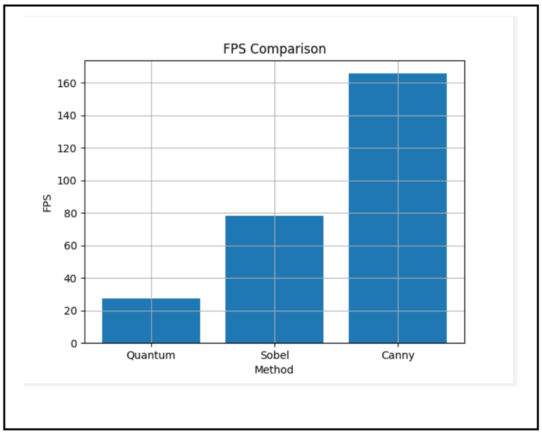

Fig. 1. FPS comparison of edge detection methods.

The classical Canny detector achieved the highest frame rate, followed by Sobel, while the proposed frequency-domain approach exhibited a lower FPS due to additional transform operations. Despite this, the proposed system maintained real-time processing capability.

Table I summarizes the quantitative performance comparison between the evaluated methods.

TABLE I. PERFORMANCE COMPARISION OF EDGE DETECTION METHODS

METHOD	FPS	PSNR (DB)	PROCESSING SPEED	EDGE QUALITY
QUANTUM	27.51	27.57	MODERATE	SMOOTH EDGES, NOISE RESISTANT
SOBEL	78.45	27.48	FAST	STRONG GRADIENTS, SOME NOISE
CANNY	165.79	27.52	VERY FAST	SHARP EDGES, FRAGMENTED CONTOURS

The PSNR values for all methods remained within a similar range, indicating comparable overall intensity preservation as illustrated in Fig. 2.

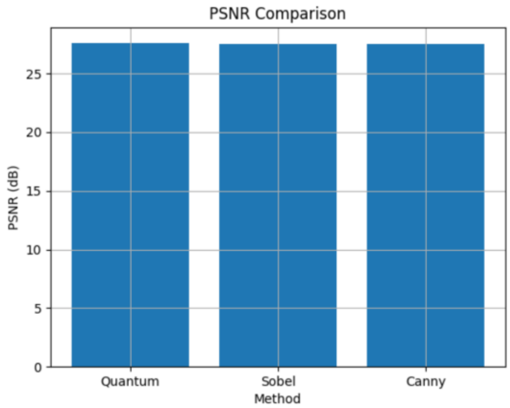

Fig. 2. PSNR comparison between evaluated methods.

This behavior is expected because PSNR evaluates global similarity rather than edge localization accuracy.

D. Visual Analysis

Qualitative comparison of output frames demonstrates that the proposed method produces smoother and more continuous edge maps, particularly in regions affected by noise or illumination variation as illustrated in Fig.3.

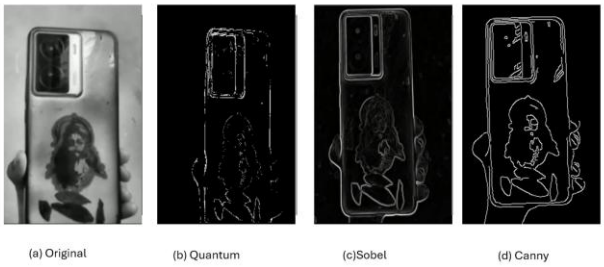

Fig. 3. Comparison of edge detection outputs: (a) original frame, (b) quantum-inspired method, (c) Sobel operator, (d) Canny detector.

The quantum-inspired method produces smoother and more continuous edge boundaries compared to Sobel and Canny, particularly in regions affected by noise and illumination variations.

Sobel detects primary gradients effectively but misses subtle edge transitions, while Canny generates sharp edges but occasionally produces fragmented contours. The quantum-inspired approach preserves fine structures and diagonal boundaries more consistently across frames.

E. Discussion

The results indicate a trade-off between computational speed and edge quality. Classical operators provide higher processing speed but are more sensitive to environmental variations such as noise and lighting changes. In contrast, the proposed frequency-domain method offers improved edge continuity and robustness at a slightly higher computational cost.

Since the system operates on real-time video streams without ground-truth annotations, evaluation focuses on computational performance and visual quality rather than pixel-level comparison metrics. The results confirm that the proposed approach is suitable for intelligent surveillance systems where stable edge extraction is more critical than maximum processing speed.

V. CONCLUSION

This paper presented a quantum-inspired edge detection framework for real-time surveillance applications using frequency-domain processing combined with classical edge operators. The proposed approach integrates preprocessing, Fourier-based transformation, and gradient-based refinement to enhance structural edge detection while maintaining computational efficiency. Experimental evaluation showed that the method produces stable and continuous edge maps under noise, illumination variations, and motion conditions while sustaining real-time performance.

Comparative results with classical methods such as Sobel and Canny indicate that although traditional operators achieve higher frame rates, the proposed frequency-domain technique provides improved edge continuity and robustness. These findings suggest that frequency-domain edge analysis is a practical solution for surveillance systems where visual stability and edge clarity are more critical than maximum processing speed.

The framework operates entirely on classical hardware while simulating quantum-inspired computation, making it suitable for real-world deployment without requiring physical quantum devices. Future work will focus on GPU-based optimization, adaptive parameter selection, and integration with intelligent video analytics modules such as object detection and activity recognition to further enhance system capability and scalability.

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