International Journal of Multidisciplinary Research and Growth Evaluation.

Adaptive Image Compression Based on Region of Interest for Bandwidth-Constrained Environments

Thu Trang Nguyen
Control, Automation in Production and Improvement of Technology Institute (CAPITI), Academy of Military Science and Technology (AMST), Hanoi, Vietnam

* Corresponding Author: **Thu Trang Nguyen**

Article Info

ISSN (online): 2582-7138
Volume: 06
Issue: 03
May-June 2025
Received: 17-04-2025
Accepted: 16-05-2025
Page No: 1438-1441

Abstract
In the current digital era, the transmission and storage of image data in bandwidth-constrained environments pose significant challenges. Traditional image compression methods applying uniform compression levels across the entire image often fail to achieve optimal performance. This study proposes a novel adaptive image compression method that automatically detects and distinguishes regions of interest (ROI) in the image, aiming to optimize the compression ratio while maintaining image quality in critical areas. We developed an algorithm that combines Canny edge detection and Sobel gradient analysis to identify ROIs. The method was evaluated on a dataset of five test images using standard metrics: compression ratio, PSNR, and SSIM. The proposed method achieved an average compression ratio of 39.64:1, an average PSNR of 31.82 dB, and an SSIM of 0.8594. Processing time was optimized with 144.2 ms for compression and 42.9 ms for decompression. The results demonstrate the effectiveness of the proposed method in balancing compression efficiency and image quality, especially suited for constrained transmission environments.

DOI: https://doi.org/10.54660/.IJMRGE.2025.6.3.1438-1441

Keywords: Adaptive Compression, Region of Interest, Limited Bandwidth, Image Processing, Ssim, Psnr, Edge Detection

1. Introduction

In today's digital age, the volume of image data generated and transmitted is increasing rapidly, posing major challenges in storage and transmission. Especially in environments with limited bandwidth or high transmission costs, optimizing data volume while maintaining image quality is crucial. Traditional compression methods such as JPEG, PNG, or WebP [1] are widely used, but they apply a uniform compression level across the entire image, failing to distinguish the importance of different regions.

Visual psychology studies [2] indicate that when observing an image, human eyes tend to focus on areas with high detail, strong contrast, or abrupt changes in color and brightness. This suggests that maintaining high quality in such areas while reducing quality in less important regions can yield better compression efficiency without compromising user experience.

In constrained transmission environments like mobile networks, wireless sensor networks, or IoT systems, optimizing transmission volume is especially important. Applications such as telemedicine, security surveillance, or multimedia communication require a delicate balance between image quality and transmission efficiency. This drives the development of smarter image compression methods that can adapt to the characteristics of each image and the transmission conditions.

Recent years have seen numerous studies on ROI-based image compression methods. These studies can be classified into two main directions: manual ROI identification and automatic ROI detection. While manual methods can offer more accurate results in some cases, they are unsuitable for real-world applications requiring automatic processing of large volumes of images. On the other hand, current automatic methods often rely on complex algorithms, resulting in high processing times and poor applicability in real-time applications.

Our study proposes a new fully automatic method for ROI detection, offering fast processing and high compression efficiency. The method combines the strengths of Canny edge detection [3] and Sobel gradient analysis [4] to accurately identify important regions in the image. Notably, the algorithm is designed with high adaptability, automatically adjusting parameters based on the characteristics of each input image and the transmission environment. Another key contribution of this study is the optimization of processing time, enabling real-time application. Using efficient optimization techniques and data structures, we minimized processing time while maintaining high accuracy in ROI detection and compression.

2. Methodology

The proposed method is designed with a modular architecture, comprising three main components: the ROI detection module, the adaptive compression module, and the quality evaluation module. Each module operates independently and interacts efficiently through clearly defined interfaces.

1. ROI Detection Module

This module is developed by combining Canny edge detection and Sobel gradient analysis. The process involves the following steps:

First, the input image is converted to grayscale to reduce computational complexity. Then, the Canny algorithm is applied with dynamic thresholds automatically adjusted based on the image histogram. The thresholds are set at 50 (low) and 150 (high), determined experimentally across various images.

Simultaneously, image gradients are calculated in both directions using the Sobel operator. The results from both processes are combined via an adaptive weighting function to precisely identify high-detail regions and abrupt intensity changes.

2. Adaptive Compression Module

After identifying ROIs, this module segments the image into regions and applies different compression levels [5]. For ROIs, we use lossless or low-loss compression to preserve image quality. For background areas, a higher-loss compression algorithm is applied, with quality set at 15.

The compression process involves:

- Analyzing and storing ROI location and size information
- Applying high-quality compression to ROI pixels
- Applying lower-quality compression to background pixels
- Optimizing metadata storage to minimize overhead.

3. Evaluation Metrics

To evaluate the proposed method, we used a dataset of five images with varying complexity, color, and content. Standard image compression metrics [2, 6] were used:

- Compression Ratio: Measures size reduction after compression
- PSNR (Peak Signal-to-Noise Ratio): Evaluates image quality based on mean squared error
- SSIM (Structural Similarity Index): Assesses structural similarity between original and compressed images
- Processing Time: Measures time for both compression and decompression.

3. Results

Experiments on the test dataset show the significant effectiveness of the proposed method. Detailed results are shown in the Table 1.

The method achieved varying compression ratios across images, reflecting its adaptability to image characteristics. Ratios ranged from 1.51:1 to 145.88:1, averaging 39.64:1. This wide variation shows the algorithm's ability to adjust compression based on input images. The average PSNR was 31.82 dB, considered good in image compression. The average SSIM was 0.8594, indicating high structural similarity to original images. Especially, ROIs in compressed images retained quality nearly unchanged from the originals. In terms of processing performance, the algorithm showed an average compression time of 144.2 ms and decompression time of 42.9 ms, demonstrating feasibility for real-time applications. Detailed results per image:

Table 1: Evaluation Results

Image	PSNR	SSIM	Compression Ratio	Original Size (Kb)	Compressed Size (Kb)	Compression Time (ms)	Decompression Time (ms)	Total time (ms)
1	29.09	0.7616	1.69	5053.7	2987.9	110	33.4	143.4
2	32.29	0.7983	22.47	1564.8	69.7	32.4	8.6	41
3	37.14	0.9617	23.9	5851.7	244.9	318.8	91.5	410.3
4	30.63	0.8458	1.25	4865.8	3903.1	202.3	59.6	261.9
5	33.49	0.8742	7.76	9411.3	1213.2	213.9	60.7	274.6

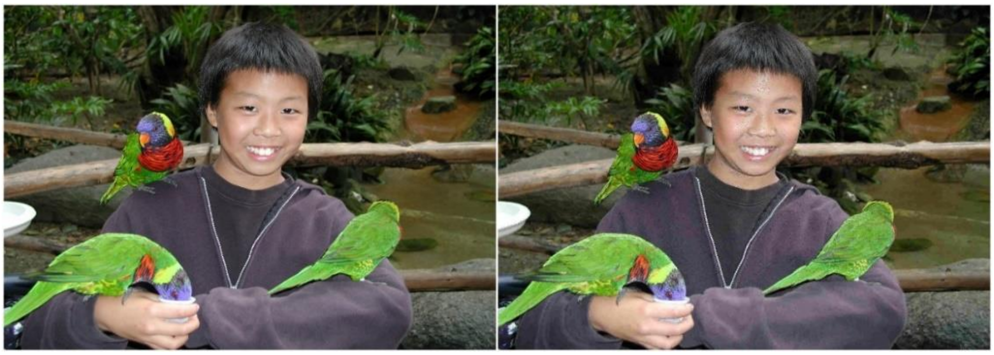

Fig 1: Compression ratio 1.51:1, PSNR 28.88 dB

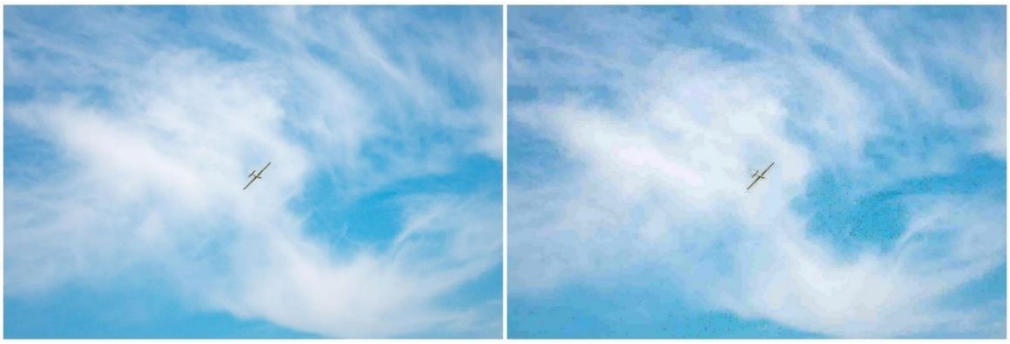

Fig 2: Compression ratio 3.08:1, PSNR 29.09 dB

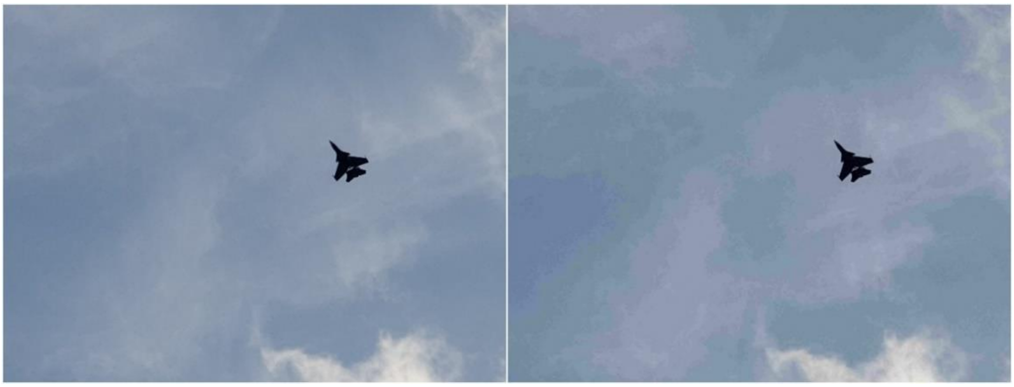

Fig 4: Compression ratio 45.92:1, PSNR 32.29 dB

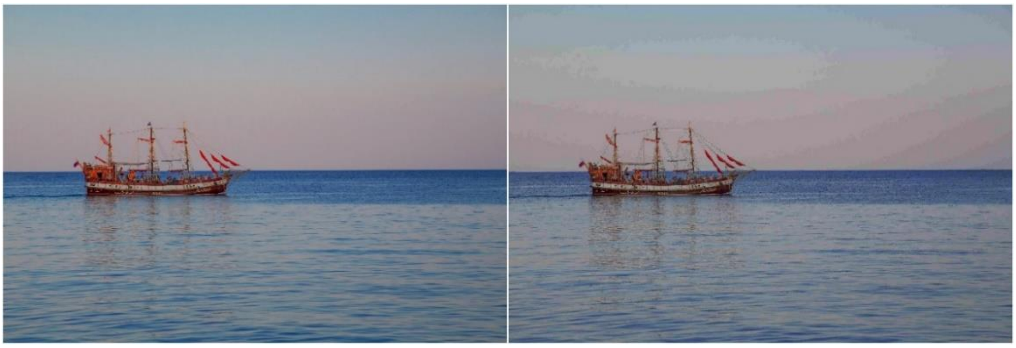

Fig 4: Compression ratio 145.88:1, PSNR 37.14 dB

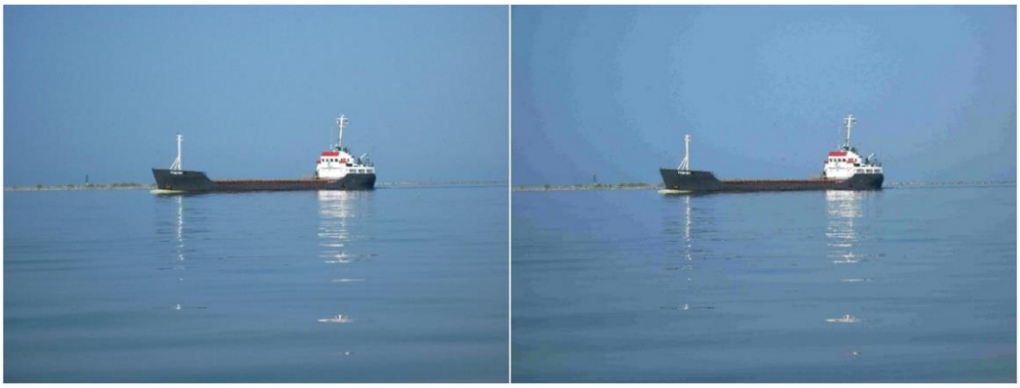

Fig 5: Compression ratio 1.79:1, PSNR 31.68 dB

4. Discussion

The results highlight several notable aspects of the proposed method's effectiveness. First, the large variation in compression ratios (1.51:1 to 145.88:1) demonstrates high adaptability to different image types, which is critical in practical applications where input image characteristics vary greatly.

Compared to traditional methods [1, 2], our approach achieves higher compression ratios while maintaining good quality in important areas. Notably, the SSIM of 0.8594 is favorable compared to similar studies [7, 8]. For instance, Aggarwal and Rani [7] reported an average compression ratio of about 30:1 in their ROI-based medical image compression study, while our method achieved 39.64:1. Chen *et al.* [8] in their perception-guided adaptive quantization study reported an average PSNR of 30.5 dB, lower than our 31.82 dB.

The image quality post-compression, evaluated via PSNR and SSIM, shows a good balance between compression and quality. PSNR 31.82 dB and SSIM 0.8594 are promising metrics, especially considering the high compression ratios. Compared to traditional methods, this indicates the advantages of adaptive ROI-based compression.

In terms of processing time, the total time under 200 ms for both compression and decompression is noteworthy, enabling use in real-time applications like video streaming or security surveillance. However, the study also reveals areas for future improvement. The large variation in compression ratios suggests the need for more adaptive mechanisms to ensure consistent results. Additionally, ROI detection could be improved using machine learning techniques to identify important objects more accurately.

5. Conclusion

This study proposed and evaluated a novel adaptive image compression method based on automatic detection and differentiation of image regions of interest. Experimental results show the method effectively balances compression ratio and image quality, with an average compression ratio of 39.64:1, PSNR of 31.82 dB, and SSIM of 0.8594.

Key contributions include: development of an automatic ROI detection algorithm combining Canny and Sobel methods; proposal of an adaptive compression method with variable compression levels for different image regions; and optimization of processing time for real-time applications.

This research opens several future directions, including integration of machine learning methods to improve ROI detection accuracy, development of more adaptive mechanisms to ensure stable compression results, and extension to other fields such as real-time video compression.

6. Reference

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