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Study and Evaluation of Digital Image Edge Detection Methods: Approaches and Techniques

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Abstract

The most important feature in an image that greatly influences its perception is the edges. In its simplest form, an edge can be defined as the location of changes in intensity and points of discontinuity in the image, which include at least a few pixels. Edge detection is the first step in many machine vision applications. It significantly reduces the amount of data, filters out irrelevant or minor information, and provides essential details about an image. This information is used in image processing for object recognition. However, challenges such as false edge detection, noise-related issues, and the absence of low-contrast boundaries still exist. Over the years, various methods and techniques have been proposed to identify edges in digital images, each with its own advantages, disadvantages, and specific applications. This paper reviews general edge detection techniques and studies and evaluates several methods introduced in recent years for digital image edge identification.

Keywords: Edge Detection, Digital Images, Object Recognition, Techniques.

Introduction

One of the useful and effective features in object recognition is the use of shape and edge information. Therefore, the use of edges is common in many machine vision and recognition applications. Considering this, it can be concluded that designing appropriate edge detectors is of special importance [9].

Undoubtedly, the most important parameter in an image that greatly affects its perception is the edges. In the simplest case, an edge can be defined as the location of intensity changes and points of discontinuity in the image, which include at least a few pixels [16]. In general, an edge is not just a local feature of the image; it also depends on the structure of the surrounding region. Moreover, according to the definition of an edge as a location of intensity changes, the range of these changes must be considered to determine the presence of an edge and its precise location. In this way, if the edges of an image are detected, the location of all prominent and faint objects in the image will be identified, and their fundamental properties, such as area, perimeter, shape structure, type, and position, can be measured and recognized by processing only the limited points of the image that correspond to edges. Consequently, using an accurate edge detector directly helps increase feature recognition rates and enables precise image segmentation [10].

Edge detection is one of the fundamental tasks in image segmentation. To divide an image into different regions, the boundaries of each region must be determined. Edge detection is used for object recognition and has numerous applications. One of the most important applications is in medical science. For instance, in medical imaging, such as MRI images where the intensity of white and gray objects are close, edge-based segmentation methods are used to generate satisfactory edges and segments [8].

Most common applications of edge detection are in machine vision and pattern recognition, where the primary task is to distinguish objects from the background. It is essential to detect edges completely to correctly extract objects, making edge detection a necessary component of image processing. One important characteristic of edge detectors is their ability to find correct edge lines in rotated images. Some edge detectors are widely used and popular, such as Sobel, Laplacian, Marr-Hildreth, and Canny [8].

Considering the importance of edges in images and edge detection for digital image processing, the present study aims to propose a method in the field of fuzzy logic for edge detection that offers higher accuracy compared to similar methods. This algorithm can be applied in a wide range of digital image processing applications. Edge detection using the fuzzy relative pixel value algorithm has proven successful in identifying edges in various images after implementing and testing the algorithm with different image sets.

This study is based on fuzzy logic. Many methods have been used for edge detection in images so far. Classical edge detection operators include Sobel, Canny, and Roberts. Among these, the Canny operator has generally produced relatively good results in most images. A limitation of these operators is that edge detection occurs locally in the image [12]. In this research, fuzzy logic is used, which is considered a novel approach in image processing. Results from various studies that employed fuzzy logic have shown better outcomes compared to classical methods. In general, due to the presence of uncertainties in many aspects of image processing, fuzzy processing is highly desirable. These uncertainties include: additive and non-additive noise at the low-level image processing stage, inaccuracies in algorithmic assumptions, and interpretational ambiguities during high-level image processing [9].

Edges in images generally correspond to abrupt changes in physical properties such as geometry, intensity, and reflectance. The goal of this study is to propose an algorithm for edge detection in images, which is based on fuzzy logic.

Lecture review

Edge Detection Techniques

One type of image processing is intermediate-level processing, where the input is an image and the output is image features such as edges. Edges are points in an image where two neighboring pixels have different intensity values.

The purpose of edge detection is to mark points in an image where the intensity changes sharply. In most edge detection methods, a local derivative operator is computed. Both first- and second-order derivatives are used to detect edges. To determine whether a pixel lies on an edge, the first derivative value is used. The first derivative of an image at each point is equal to the magnitude of the gradient. First-order derivatives produce thick edges.

The magnitude and direction of an edge at a location (x, y) in an image f are referred to as the gradient. Masks or filters are represented as matrices, where all neighboring pixels are multiplied by their corresponding coefficients, and the results are summed. Derivatives along the x and y axes are computed using the neighborhood of the matrices.

One common edge detection method is gradient computation. To obtain the image gradient, the partial derivatives along the x-axis and y-axis must be calculated at each pixel location in the image. If the pixels in the upper row of the neighborhood are subtracted from the pixels in the lower row, the partial derivative along the x-axis is obtained. Similarly, if the pixels on the left are subtracted from the pixels on the right, the partial derivative along the y-axis is obtained.

Types of Edge Detection Techniques

The following introduces some common edge detection techniques:

Roberts Cross Filter

The Roberts Cross filter is one of the earliest edge detection methods, using two 2×2 matrices. This filter is designed for two-dimensional masks with diagonal emphasis and is based on the implementation of diagonal differences [10][18].

$$|G| = |p_1 - p_4| + |p_2 - p_3|$$

$$\nabla I(x,y) = G(x,y) = \sqrt{G_x^2 + G_y^2}$$

$$\theta(x,y) = \tanh^{-1}\left(\frac{G_y(x,y)}{G_x(x,y)}\right)$$

P_1	P_2
P_3	P_4

1	0
0	-1

G_x

0	-1
1	0

G_y

Figure 1: Robert Diagonal Filter

- Pruitt Filter

This filter also uses the first derivative to find edges. It is one of the filters that is symmetrical around the central point. In this method, two 3x3 filters are used to find vertical and horizontal edges [18].

P_1	P_2
P_3	P_4

1	0
0	-1

G_x

0	-1
1	0

G_y

Figure 2: Horizontal and vertical prow

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

- **Sobel Filter**

  This filter uses the first derivative to detect edges in images. It employs the following matrices, known as **Sobel edge filters**, to find vertical and horizontal edges in an image. The GyG_yGy filter detects horizontal edges, while the GxG_xGx filter detects vertical edges. By combining these two filters, all horizontal and vertical edges in the image can be detected.

- $|G| = |G_x| + |G_y|$
- $|G| = \sqrt{G_x + G_y}$

P_1	P_2	P_3
P_4	P_5	P_6
P_7	P_8	P_9

-1	0	1
-2	0	2
-1	0	1

G_x

1	2	1
0	0	0
-1	-2	-1

G_y

Figure 3: Horizontal and vertical subshell

If we want to detect only horizontal edges, the value of the GyG_yGy filter is compared to a threshold, and the corresponding pixel is considered an edge. Similarly, to detect only vertical edges, the value of the GxG_xGx filter is compared to the threshold, and the pixel is marked as an edge. To detect both horizontal and vertical edges, the gradient magnitude GGG is computed and compared to the threshold [18].

- Canny Filter

The Canny edge detection method works by first applying a low-pass filter derived from the Gaussian function to reduce noise in the image. Then, a high-pass filter is applied in a similar manner to enhance the edges of the image. Two threshold values are selected on the histogram of the resulting image: pixels below the lower threshold are classified as non-edges, while pixels above the upper threshold are classified as edges. For pixels between the two thresholds, Canny determines edge presence based on their orientation in the image, and finally, edge thinning is performed [10].

- Fuzzy Image Processing

Fuzzy image processing encompasses all methods that perceive, process, segment, and reconstruct images and their features as fuzzy sets. The reconstruction and processing depend on the chosen fuzzy technique. Fuzzy image processing consists of three main stages: fuzzification of the image, modification of fuzzy membership values, and defuzzification [9].

Edge detection involves finding a series of connected points that exist between two segmented regions. When the regions in some images differ sufficiently in intensity and color, edge detection can be effectively used for segmentation. However, in most images, the differences in intensity and color between regions and objects are insufficient, resulting in discrete points after edge detection, which is not satisfactory for segmentation. Therefore, edge detection alone may not be suitable for segmenting some images. Nonetheless, edge detection serves as an auxiliary tool in image segmentation algorithms and, after applying preprocessing steps to enhance intensity, color, contrast, etc., can effectively contribute to segmentation [9].

- Analog Image Processing

Analog image processing refers to altering an image through electrical means. The most common example is television images. A television signal is a voltage level that fluctuates to represent brightness in the image. By electrically modifying the signal, the appearance of the displayed image changes. Brightness and contrast controls on a television adjust the signal oscillation and reference, resulting in variations in brightness and contrast of the displayed image [17].

- Fuzzy Image Processing Structure

Fuzzy image processing is not a single theory but a collection of approaches that perceive, represent, and process images, regions, and their features as fuzzy sets. The representation and processing depend on the chosen fuzzy method and the specific problem being addressed. Fuzzy image processing has three main stages: fuzzification of the image, modification of membership values, and, if necessary, defuzzification, as shown in Figure 2-1(a). Fuzzification and defuzzification stages are often inaccessible due to fuzzy hardware limitations. Therefore, encoding the image data and decoding the results are essential for enabling fuzzy image processing. The primary strength of fuzzy image processing lies in the intermediate stage, i.e., modification of membership values [21].

Image data are first transformed from the grayscale plane to the fuzzy membership plane (fuzzification). Appropriate fuzzy techniques then modify the membership values, which may involve fuzzy clustering, rule-based fuzzy methods, fuzzy combination methods, and similar approaches [10].

2-4-1 Fuzzy Edge Detection Techniques

Numerous algorithms have been proposed for edge detection in image processing. Many of these algorithms are based on image derivatives. Newer approaches, such as fuzzy and morphological methods, use mathematical operators without relying on derivatives. Edge detection is often employed in image segmentation. Fuzzy logic is a type of logic that replaces simpler machine patterns with diverse inference methods similar to human reasoning [3].

Fuzzy Image Processing (FIP) refers to a set of fuzzy approaches for image processing. In general, fuzzy image processing includes all methods that perceive, represent, and process images, regions, and their features as fuzzy sets. The representation and processing of images depend on the selected fuzzy technique and the problem to be solved. Some general observations regarding fuzzy logic in edge detection include:

- Fuzzy logic is easy to understand: The mathematical concepts behind fuzzy reasoning are simple. Fuzzy logic provides a visual, straightforward, and flexible approach. It can be easily adapted to a given system and extended for layering without starting from scratch.
- Fuzzy logic tolerates uncertain data: In real-world scenarios, many things are uncertain. Information that appears precise initially may not be accurate upon closer inspection. Fuzzy logic enables the system to manage such uncertainties.
- Fuzzy logic can be based on expert knowledge: It relies on the experience of experts familiar with the system's behavior and performance.
- Fuzzy logic can model complex nonlinear functions: A fuzzy system can match any set of input-output data. This process is facilitated by adaptive techniques such as Adaptive Neuro-Fuzzy Inference Systems (ANFIS), available in fuzzy toolboxes.

Khalili and Aghagolzadeh published an article titled Edge Detection in Images Using Local Entropy and Optimal Thresholding. The use of local entropy for edge detection has attracted attention in previous research; however, the proposed algorithm was highly dependent on the threshold parameter. To address this issue, they proposed a method based on the OTSU algorithm to determine the optimal threshold for local entropy-based edge detection. Simulation results demonstrated the efficiency of their algorithm in edge detection [3].

Karimi published an article in the Journal of Biomedical Engineering titled Edge Detection in Digital Images Using Fuzzy Techniques. He argued that fuzzy techniques serve as operators designed to simulate mathematical levels of compensatory behavior in decision-making or subjective assessment. The article introduced such an operator for computer vision applications. Karimi proposed a novel method based on fuzzy logic reasoning for edge detection in digital images without requiring threshold selection. The method begins by segmenting the image into regions using a 3×3 binary matrix. Edge pixels are mapped to distinct value ranges. The reliability of the proposed method was compared with the linear Sobel operator for different images. This method resulted in smoother and more continuous lines for straight edges and rounded curves for curved lines, while image corners were sharper and well-defined [10].

Gholami, in his master's thesis, researched edge enhancement in color images using multiscale and region-growing techniques. For this study, edge detection was essential. He emphasized that edge detection is a key component of image segmentation, playing a fundamental role in object recognition and image processing. Since most edge detectors extract edges as disconnected pixels, and some methods that extract continuous edges may also produce additional edges, researchers have sought to approximate human visual perception in edge detection. To enable computer systems to detect object edges, it is necessary first to define the color space of the image, then smooth the image and reduce noise effects.

Ali Doost and Zeynali published an article titled Sub-Pixel Accurate Edge Detection. They considered edge detection one of the most important problems in image processing and machine vision. Edge detection is a low-level process in image processing, and the performance of higher-level processes such as object recognition, segmentation, and image coding directly depends on its efficiency. For practical applications requiring high precision, sub-pixel edge detection is introduced. In their study, three sub-pixel edge detection methods were presented and compared. Simulation results were first examined for an ideal image, then for noisy images with different standard deviations. The second method, based on minimum error, was identified as the most accurate [7].

Walad and Shetty, in their article Vehicle Edge Detection Based on Fuzzy Logic Using Triangular and Trapezoidal Membership Functions, proposed a new method for vehicle image edge detection. They noted that in digital images, three types of discontinuities exist: point, line, and edge. The most common method is using spatial masks designed to detect these discontinuities. Among these, edge detection is particularly important as it forms a crucial part of image segmentation. Edge detection essentially segments an image into regions based on discontinuities, and increasing the repetition of these discontinuities allows improvement of perceived image quality under defined conditions. Edge detection using differential operators enables detection of changes in grayscale gradients or color surfaces. It is classified into two main categories: first-order edge detection (e.g., Sobel, Roberts, Prewitt) and second-order edge detection (e.g., Laplacian, Canny). Since image edges are often affected by noise, developing effective edge detection algorithms is essential. Traditional methods such as Sobel, Prewitt, and Roberts are sensitive to noise, so newer algorithms including Canny, morphological operators, neural networks, and fuzzy logic have been applied. In their study, a simple, flexible, and efficient fuzzy logic-based algorithm was implemented in MATLAB for detecting vehicle edges using a 2×2 mask. Trapezoidal and triangular membership functions of a Mamdani FIS were used for four inputs (two fuzzy sets) and one output (one fuzzy set). The 2×2 mask slides over the entire input vehicle image, and pixel values within the masks are evaluated through ten rules defined in the FIS rule editor. Based on these rules, the fuzzy output decides whether a pixel is an edge. A Gaussian filter was applied to enhance results. Experimental results demonstrated the algorithm's ability to detect thin edges in vehicle images [20].

Selit introduced a fuzzy logic-based edge detection technique for grayscale images. Edge detection is a fundamental process in many image processing and computer vision applications such as object recognition and extraction. Edge detection identifies important events in an image where significant pixel intensity changes occur. Various edge detection techniques, such as Sobel, Canny, and Prewitt, have been proposed. In this study, a fuzzy inference system-based edge detection technique was presented. Since fuzzy logic is a powerful tool for managing uncertainty, it can help decide whether a specific pixel should be considered an edge. A two-stage fuzzy inference system was proposed: the first stage evaluates pixel intensity discontinuities along different directions, while the second stage makes the final decision based on first-stage results. The proposed algorithm was implemented in MATLAB, and experimental results demonstrated improved performance compared to other edge detection techniques [19].

Hang et al. published an article titled Edge Detection in UAV Remote Sensing Images Using Zernike Moment Integration with Clustering Algorithms. Considering UAV remote sensing images (UAVRSI) with textured regions containing ground objects and distinct phenomena, traditional edge detection operators struggle to efficiently extract edge information due to varying object spectra. To address this, they proposed a UAVRSI edge detection method combining Zernike moments with clustering algorithms. First, two common clustering algorithms—the C-means and K-means approaches—were applied to segment homogeneous ground object regions in the original images. Then, Zernike moments were used to detect edges on the clustered remote sensing images. Comparative and visual sensitivity methods were used to evaluate edge detection accuracy. Two experimental datasets were selected to assess the proposed method. Results showed that the method effectively improved the accuracy of edge information extracted from remote sensing images [14].

Research Methods

In this study, a novel method for edge detection in digital images using fuzzy logic is introduced. Fuzzy logic is a key concept in modern artificial intelligence and aids in the implementation of relative pixel value algorithms. It also helps identify and highlight all edges in an image by examining the relative pixel values, thereby providing an algorithm that summarizes concepts from digital image processing and artificial intelligence. A full scan of the image is performed using a windowing approach, which is exposed to a set of fuzzy states to compare pixel values with their neighboring pixels in order to evaluate the pixel gradient within the window. After examining the fuzzy states, appropriate values are assigned to the pixels in the window, which ensures that the image is prepared with all relevant edges detected.

Fuzzy image processing is a combination of fuzzy approaches for image processing. It consists of three main stages: fuzzification of the image, modification of membership values, and defuzzification. The fuzzification and defuzzification stages enable image processing using fuzzy techniques. The main strength of fuzzy image processing lies in the intermediate stage, i.e., the modification of membership values. Once the image data are transformed from the color plane to the membership plane (fuzzification), appropriate fuzzy techniques adjust the membership values. This adjustment can involve fuzzy clustering, rule-based fuzzy methods, fuzzy aggregation approaches, and similar techniques [14].

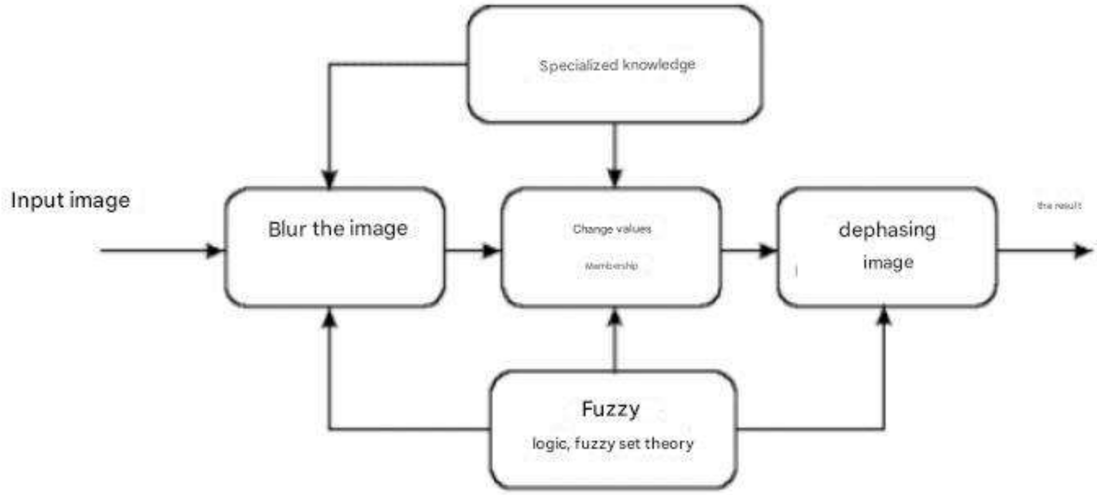

Figure 4: General structure of fuzzy image processing

Data analysis

Fuzzy Membership Functions

In a fuzzy inference system, membership functions (MFs) play a key role. In a fuzzy set, fuzzification is measured using MFs because they are fundamental components of fuzzy set theory. The type and shape of the MF must be carefully chosen, as they affect the performance of the fuzzy inference system. Trapezoidal MFs are used for input data, as they provide improved logical results compared to other MFs, while Gaussian MFs are used for output data because they are smooth and non-zero at all points.

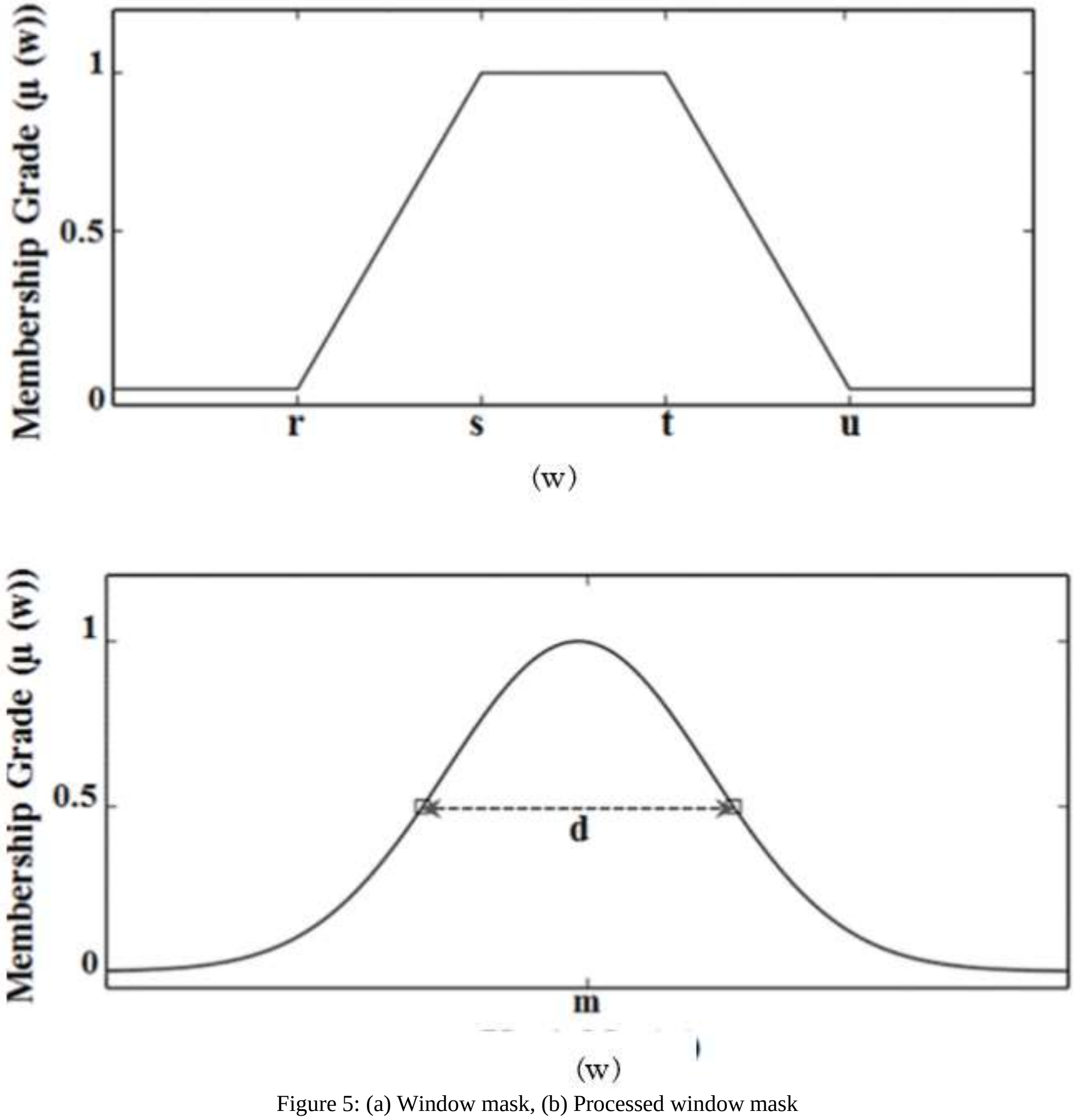

Figure 5: (a) Window mask, (b) Processed window mask

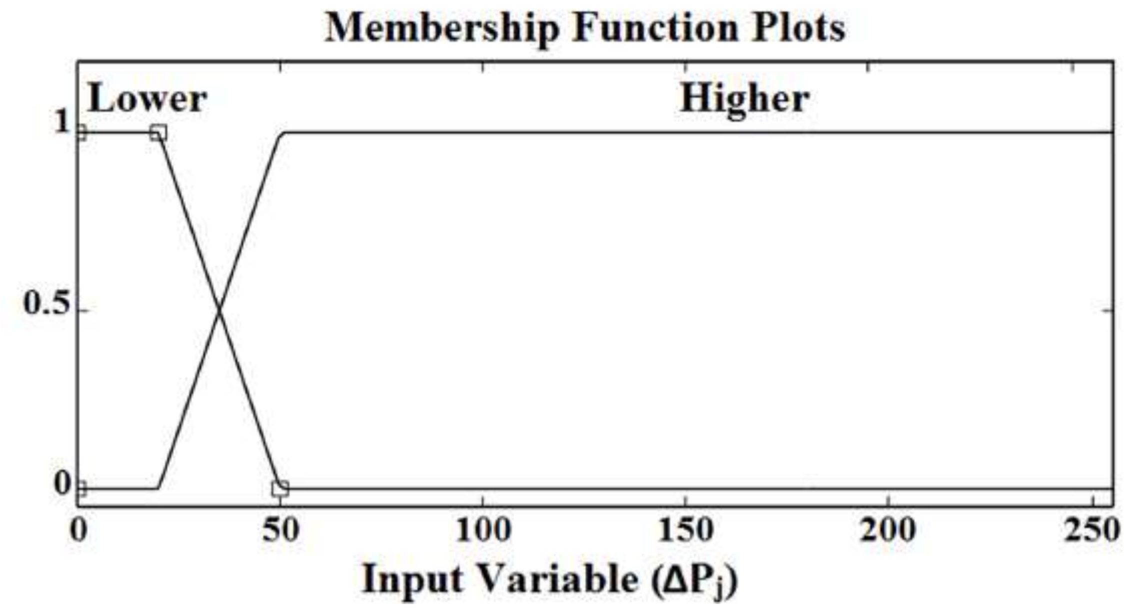

Figure 6: MF designs, (a) Trapezoidal, (b) Gaussian

The standard trapezoidal membership function
$T\ r\ z\ F$

$$T_{rz}F\ (w; r, s, t, u) = \begin{cases} 0 & (w < r) or (w > u) \\ \dfrac{z-r}{s-r} & r \le w \le s \\ 1 & s \le w \le t \\ \dfrac{u-z}{u-t} & t \le w \le u \end{cases}$$

F is defined as follows:
[equation placeholder]
[equation placeholder]
where
$r\ ,\ s,\ t\ ,$

$$\mathrm{GF}\,(\mathrm{w}; \mathrm{m}, \mathrm{d}) = \mathrm{e}^{-\frac{(\mathrm{w}-\mathrm{m})^2}{2\mathrm{d}^2}}.$$

r,s,t, and u are parameters of the trapezoidal MF, as illustrated in Figure 3-3.
The Gaussian MF is expressed as:
[equation placeholder]

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[equation placeholder]

Figure 3-4: Input variable MFs

ΔPjΔP j where m and d are parameters of the Gaussian MF [20].

Comparison of the Proposed Method with Other Methods

The fuzzy relative pixel value algorithm for edge detection was tested on satellite images, and its outputs were compared with outputs from existing edge detection algorithms. The results indicated that the algorithm produced much clearer edges than the other algorithms and was significantly more successful in edge detection.

Figure 7: Input satellite image

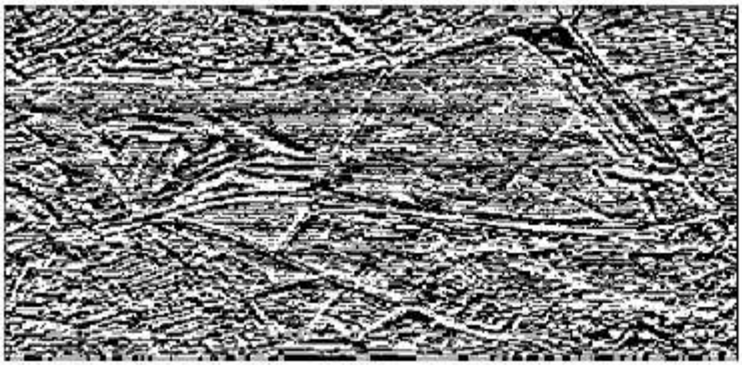


Figure 8: Output using horizontal Sobel operator

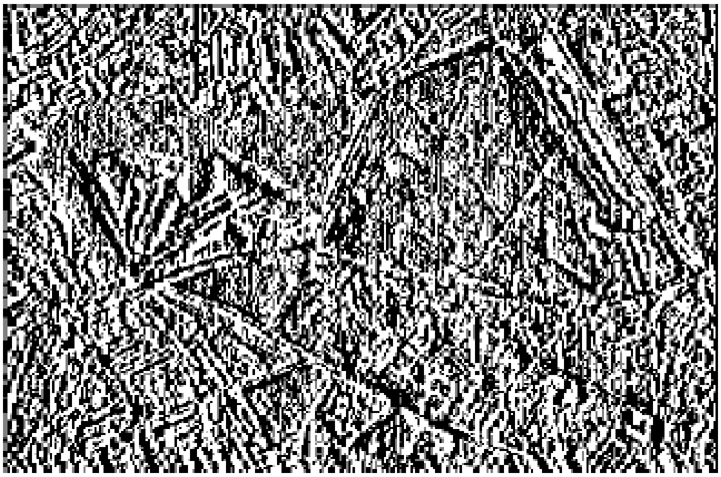


Figure 9: Output using vertical Sobel operator

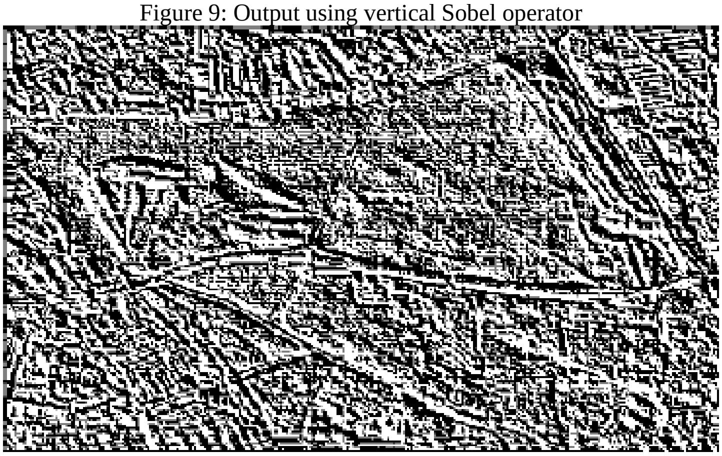


Figure 10: Output using Sobel 45°+ operator

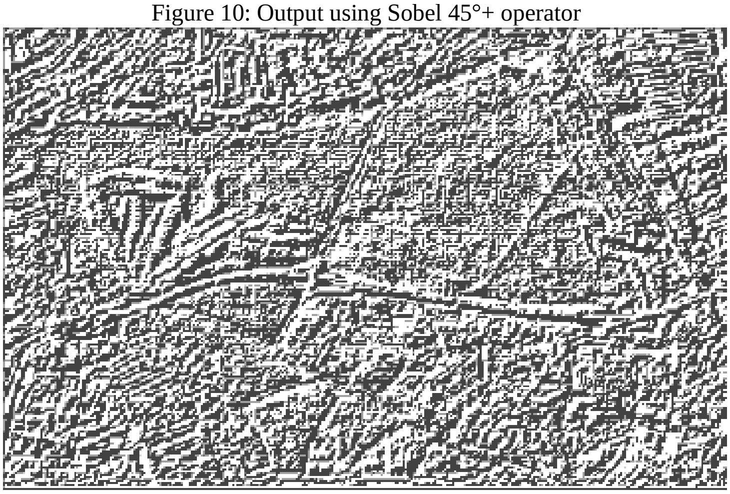


Figure 11: Output using Sobel 45°− operator

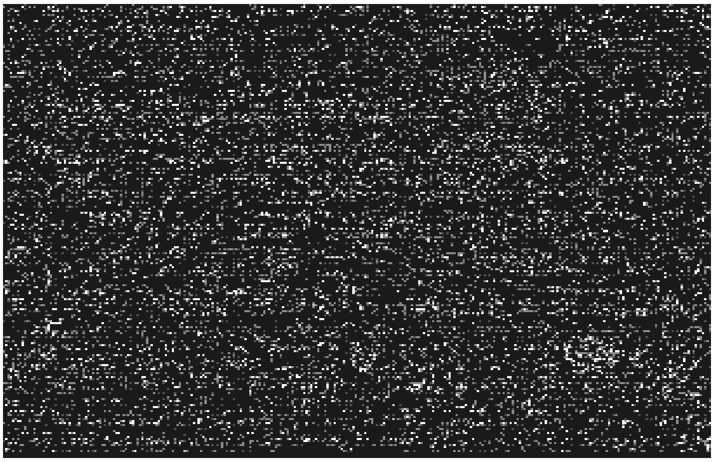


Figure 12: Intermediate image

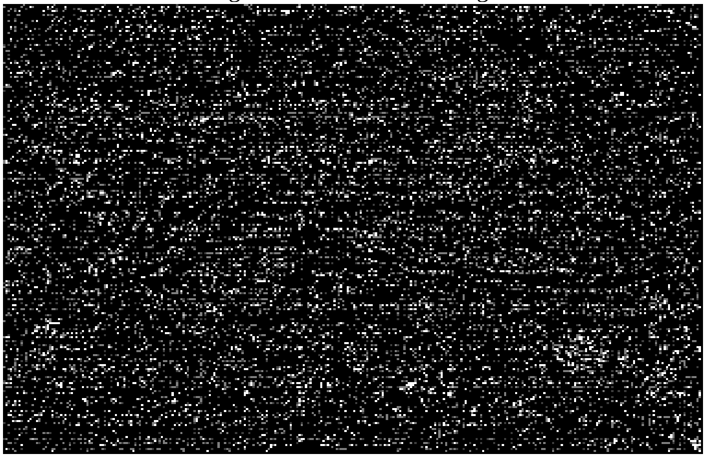


Figure 13: Output of the fuzzy relative pixel value algorithm

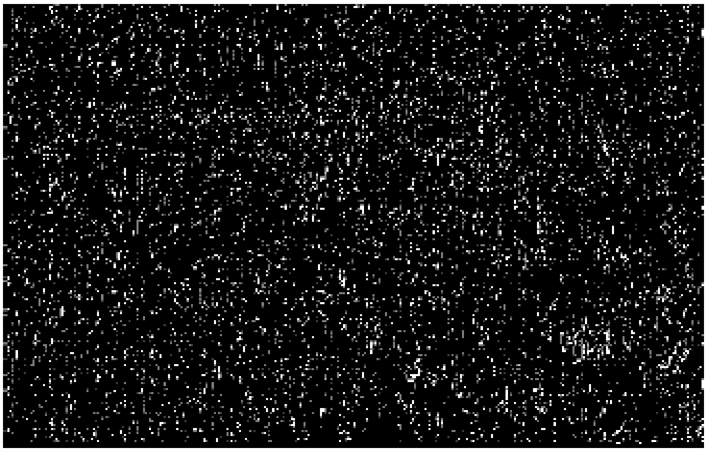


Figure 14: Another output from the fuzzy relative pixel value algorithm

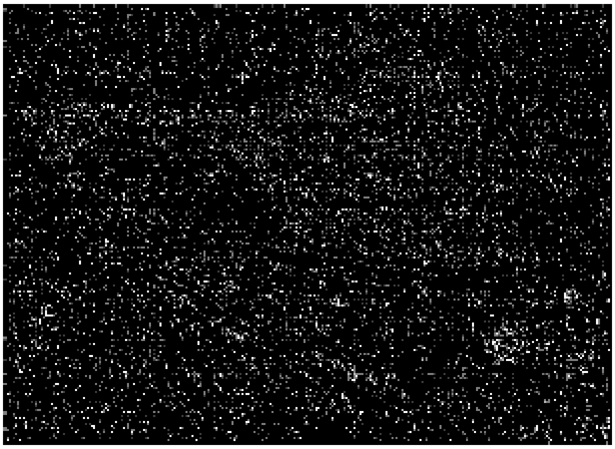


Figure 15: Another output from the fuzzy relative pixel value algorithm

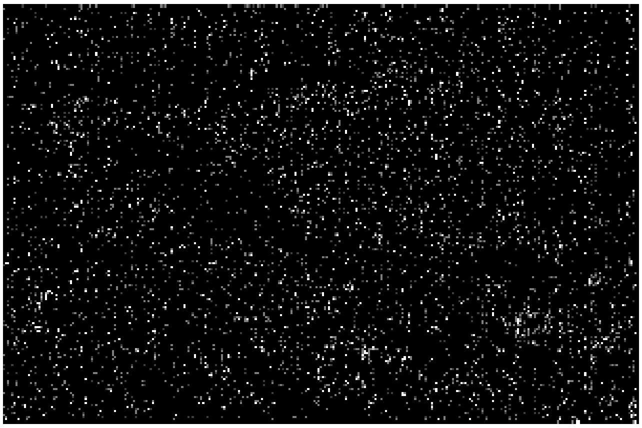


Figure 16: Another output from the fuzzy relative pixel value algorithm

The output of the proposed algorithm was compared with the outputs of various Sobel algorithms. It was observed that the edges produced by the fuzzy method were clearer than those detected by the other algorithms. Therefore, the fuzzy relative pixel value algorithm provides better edge detection and a comprehensive set of fuzzy conditions, greatly assisting in high-efficiency edge extraction.

The following are additional sample outputs of the proposed algorithm compared to other algorithms:

Figure 17: Input image

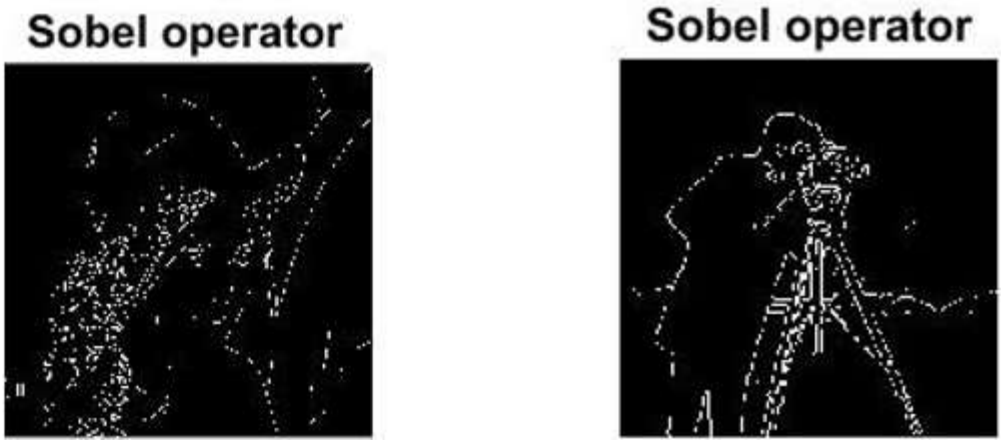
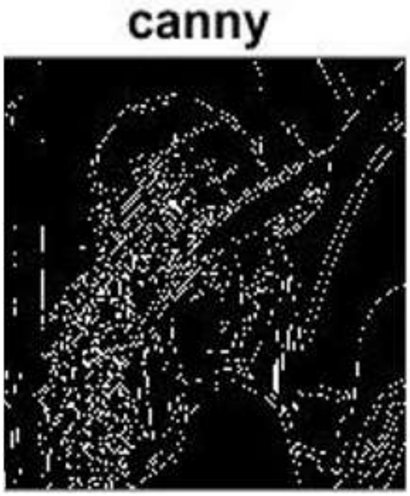


Figure 18: Output using Sobel operator

Figure 19: Output using Prewitt operator

Figure 20: Output using Robert operator



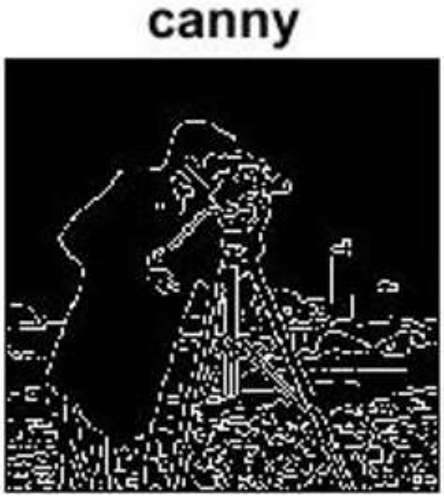


Figure 21: Output using Canny operator

Conclusions

The proposed system was tested on various images, and its performance was compared with that of different operators. The output results clearly demonstrated the superiority of the proposed algorithm over previously used edge detection algorithms. Due to the uncertainty present in many aspects of image processing, fuzzy processing is desirable because of its tolerance to such uncertainty. This uncertainty includes additive and non-additive noise in raw image processing, undefined assumptions in algorithmic frameworks, and interpretational ambiguities during high-level image processing.

In conventional edge detection processes, edges are often modeled as intensity ridges. However, in practice, this assumption is only approximately valid, which leads to limitations in the algorithm—this is the main drawback [14]. Fuzzy image processing represents a formulated expression of expert knowledge about edges and combines uncertain information from multiple sources. Designed fuzzy rules provide an effective solution for enhancing edge quality as much as possible. One limitation of previous algorithms was their extensive computational requirements.

The results allow the following conclusions:

- The implemented FIS system offers greater robustness to variations in contrast and brightness, while also avoiding double-edge detection.
- The proposed algorithm demonstrated stable smoothness and straightness for lines and provided accurate curvature for curved lines. At the same time, corners were clearly defined and easily identifiable.

So far, no research has compared the performance of Type-1 and Type-2 fuzzy algorithms or compared morphological and fuzzy algorithms, leaving the relative advantages of these methods undetermined.

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