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A Comparative Study of Fuzzy Logic Type-1, Type-2 and Gradient-Based Method for Edge Detection in RGB Images

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Abstract:

Edge detection is widely used in image processing to simplify the images by reducing data. It emphasizes essential features and thereby enhances data processing speed. Edge detection techniques are widely used in the fields of Medical Imaging, Vehicle Detection, Fingerprint Recognition, Robotic vision, Steganography, Feature extraction, security etc. This research paper presents a comparative analysis of different edge detection techniques based on gradient fuzzy Type-1 and fuzzy Type-2. The researcher has experimentally evaluated the edges detected using Prewitt operator based on Gradients, mshEdgeRGB_T1 algorithm based on Fuzzy Type-1 Logic and mshEdgeRGB_T2 algorithm based on Fuzzy Type-2 Logic. The results reveal that edge pixels detected by using algorithms based on Fuzzy Logic are more in comparison to Gradient based Prewitt operator. The paper also shows a comparative analysis of edges detected by algorithms based on Fuzzy Logic for different ranges of membership values of pixels in fuzzy edge set.

Keywords: Fuzzy Type-1 Logic, Fuzzy Type-2 Logic, Edge Detection, Prewitt Operator.

1. Introduction

Edge detection is crucial in image analysis, playing a key role in fields such as feature extraction, image segmentation and pattern recognition. This makes edge detection a fundamental process in the field of image processing [4]. Edges are the visible lines that separate different objects or textures in an image. They are, where the image changes quickly from one colour or brightness to another. In terms of frequency, edges have higher frequencies compared to other parts of the image [1]. In recent decades, most of the research work focused on edge-detection algorithms for grayscale images. However, colour image processing has gained more attention these days because it provides more detailed information about objects in a scene, enhancing image processing performance. While edge detection in colour images is more complex computationally, it offers significant advantages, such as improved object location accuracy and the ability to process more complex images [2].

Image Edge detection can broadly be categorized into two types i.e. Gradient-based and Gaussian-based edge detectors. Gradient-based edge operators include Canny, Sobel and Prewitt operators, while Gaussian-based edge operators include Laplacian of Gaussian (LOG) operators. The Gradient-based edge detectors calculate first-order derivatives and Gaussian-based edge detectors calculate the second order derivatives of image pixels to find the edges of any digital image [6]. In this paper, we used

Gradient-based Prewitt operator for comparison with algorithms based on Fuzzy Type-1 and Fuzzy Type-2 Logic.

In a wide range of important applications, edge detection and image segmentation techniques are frequently used. Fuzzy rule-based classifiers have been employed in various tasks, including self-localization and landmark identification, data density estimation, real-time object detection and human activity recognition [7]. In this paper, we evaluate edge detection algorithms based on Fuzzy Type-1 and Fuzzy Type-2 inference systems and show the comparison to analyse that algorithm which detects more edge pixels. The experimental results are compared for PSNR, MSE and energy ratio.

Balochain et al. worked on the classical Prewitt Operator, calculating the derivatives along the x and y directions using Fractional Order Derivative (FOD) to improve edge detection capability [1]. In [2], Gonzalez presented a new method of edge detection for colour images, combining fuzzy type-1 and gradient-based edge detection. This proposed method can handle a higher degree of uncertainty in edge detection and provides sharper edges compared to gradient-based edge detectors. Yau Hwang et al. [5] proposed a new fuzzy Sobel method that can detect and enhance the edges of an image by determining threshold values. In this method, the gradient value is still calculated, but the threshold value is replaced according to the fuzzy rule. Wang et al. [8] proposed a fuzzy logic method for edge detection, focusing on different membership values to create a new model for clear image identification. Their experimental results were compared with traditional operators like Canny and Sobel. Zhang et al. [9] proposed a new edge detection technique based on a fuzzy logic system known as adaptive neuro-fuzzy. This technique uses a sharpening Gabor filter to regulate edge quality and a Gaussian filter to reduce noise caused by sharpening.

Recently, a new method of edge detection for RGB images was proposed which is based on fuzzy type-1 and Sobel operator Yau Hawng et al. [5]. Motivated by the work done in this field, the present study exploits ***mshEdgeRGB_T1*** and ***mshEdgeRGB_T2*** based on Fuzzy Type-1 and Fuzzy Type-2 Logic respectively and Prewitt operator for comparative analysis of detected edges in RGB images.

2. Methods

2.1 Prewitt operator

This operator was introduced by Granzales, Edds and Wood, which is based on a first-order derivative operator. It is also known as a Gradient-based operator whose primary goal in image processing is to detect edges and recognize the shapes within the image [10]. The operator can be applied to all types of images and is particularly effective in detecting sharp edges. The operator used in image processing to find edge pixels, designed to identify areas in an image where the intensity changes sharply, typically indicative of edges. The algorithm approximates the gradient of the image intensity function at each point, highlighting the orientation and strength of edges [11].

Horizontal Convolution Kernel (P_X)		
1	**1**	**1**
0	**0**	**0**
-1	**-1**	**-1**

The Prewitt operator uses two 3x3 convolution kernels, one for detecting an edge in horizontal direction **(P_X)** and second for vertical direction **(Py)**, which are shown below:

Vertical Convolution Kernel (Py)		
1	**0**	**-1**
1	**0**	**-1**
1	**0**	**-1**

these masks are applied on a colour image to calculate the change in intensity value of every pixels in both directions. The sum of these masks is zero. When we apply both kernels of an image it works to solve the first-order derivative and calculate the difference between pixel intensities in the edges area. Using **Px** and **Py,** we find the gradient magnitude as well as the direction of edge. It is the best method to find the orientation, brightness changes, intensity value, shape and boundaries of any image [12].

2.2 Fuzzy Type-1 Logic System

Fuzzy Type-1 logic is introduced by Professor Lofti Zadeh in the 1960s. Fuzzy Type-1 gives a powerful framework for image processing by incorporating the concept of partial membership, which contrasts with the binary nature of classical sets. In this context, each pixel in an image is assigned a membership value between 0 and 1, reflecting its degree of belonging to different categories such as edges, textures or background. This approach enables more precise and adaptive processing by capturing the inherent vagueness and variations in image data. For instance, in tasks like edge detection, Fuzzy Type-1 sets facilitate the identification of edges that may be blurred or not sharply defined, thereby improving the accuracy of boundary delineation. Their ability to model uncertainty and handle gradual transitions makes Fuzzy Type-1 sets particularly effective in complex image processing applications, leading to enhanced performance and more reliable results in diverse imaging scenarios [5],[7].

2.3 Fuzzy Type-2 Logic System

Fuzzy Type-2 logic proposed by Dr. Jerry Mendel in the late 1990s, extends the capabilities of fuzzy logic in image processing by introducing a higher level of complexity and flexibility through their use of fuzzy membership functions that are themselves fuzzy. This means that rather than having a single membership value for each pixel, Type-2 fuzzy sets incorporate a range of possible membership values, providing a more nuanced representation of uncertainty and ambiguity in image data. This is particularly advantageous in scenarios involving noisy or imperfect images, where the boundaries between different regions are not clearly defined. For example, in image segmentation and edge detection, Fuzzy Type-2 sets can more effectively handle overlapping or indistinct boundaries by modelling the uncertainty inherent in pixel classification. As a result, this approach improves the robustness and accuracy of image processing algorithms, leading to enhanced image analysis and feature extraction performance.

The key difference between Fuzzy Type-1 and Fuzzy Type-2 Logic for edge detection lies in their capacity to represent uncertainties within membership functions and their approaches for handling uncertainties within membership functions, which directly impacts the accuracy and complexity of edge detection [3].

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3. Experiment and Results

This section represents the comparison between Fuzzy Type-1 and Fuzzy Type-2 Logic based edge detection of colour images using ***mshEdgeRGB_T1*** and ***mshEdgeRGB_T2*** algorithms. Research have taken three different colour images (Parrot, Apple and Flower) for experimental results and the algorithms based on Fuzzy Type-1 and Fuzzy Type-2 Logic are implemented using MATLAB software.

Fig. 1 shows the edge detected using the Prewitt operator, ***mshEdgeRGB_T1*** and ***mshEdgeRGB_T2*** edge detection algorithms. It shows that ***mshEdgeRGB_T1*** detects more edges than Prewitt operator and ***mshEdgeRGB_T2*** gives sharp edges as compared to other two methods discussed previously.

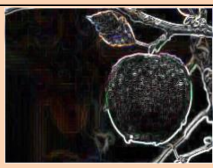
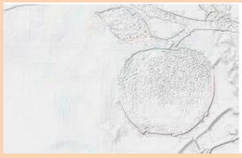
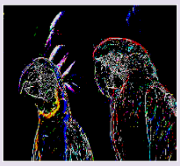
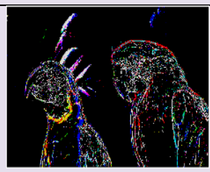
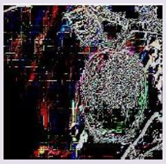
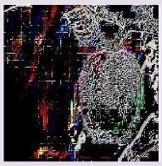
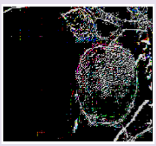
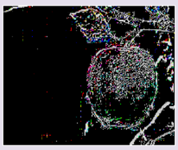
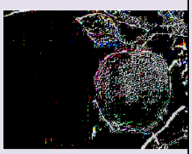
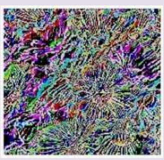
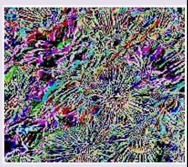
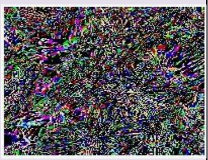
Sr. No.	Image Name	Original Image	Prewitt Operator	*mshEdgeRGB_T1*	*mshEdgeRGB_T2*
1.	**Parrot**				
2.	**Apple**				
3.	**Flower**				

Fig. 1 Edge Detection using Different Edge Detection Methods

Fig. 2 gives comparative analysis of edges detected in different image using ***mshEdgeRGB_T1*** and ***mshEdgeRGB_T2*** algorithms for different ranges of degree of membership values. It demonstrates the variations in edges detected for three different images, for membership values ranging from 0.5-0.9, 0.6-0.9, 0.7-0.9, 0.8-0.9 and 0.9-1.0. This comparative analysis highlights the distinct characteristics of each algorithm. As shown in **Fig. 2**, ***mshEdgeRGB_T1*** algorithm tends to produce smoother and more continuous edges. The ***mshEdgeRGB_T2*** algorithm gives sharper edges as compared to the results from the ***mshEdgeRGB_T1*** algorithm. Both algorithms are based on the Mamdani fuzzy inference system. To define the crisp values in the fuzzy system for input, these algorithms use the horizontal and vertical differences of pixel intensities of image. For fuzzy inference rules, four rules are applied to determine the degree of membership of pixels in three different fuzzy sets i.e. White, Gray and Black. In defuzzification, the centroid method is used to aggregate all input values and provide a single crisp value.

Table 1 demonstrate a comparative analysis between two image processing algorithms, ***mshEdgeRGB_T1*** and ***mshEdgeRGB_T2***, across various membership values (0.5-1.0) for three images: Parrot, Apple, and Flower. Evaluation parameters include Edge Pixels, PSNR (Peak Signal-to-Noise Ratio), MSE (Mean Squared Error), and L2RAT (Energy Ratio). They are used to show the similarity between the edge image using Prewitt, ***mshEdgeRGB_T1*** and ***mshEdgeRGB_T2*** algorithms. These metrics are applied on both edge image obtained from Prewitt operator and Algorithms. At the highest membership value (0.9-1.0), ***mshEdgeRGB_T2*** algorithm gives in lower PSNR value. Similarly, for the Apple and Flower images, ***mshEdgeRGB_T1*** shows better edge detection and higher PSNR, except at the highest membership value where ***mshEdgeRGB_T2*** significantly improves. At high membership value ***mshEdgeRGB_***T2 give sharp edge and low PSNR and high MSE values for all image.

When the membership value increases from 0.5-0.9 to 0.9-1.0, the number of edge pixels typically decreases, while PSNR (Peak Signal-to-Noise Ratio) generally improves and MSE (Mean Squared Error) decreases.

Image Name	**Edge Detection Type**	**Different Membership Value**				
		0.5-0.9	**0.6-0.9**	**0.7-0.9**	**0.8-0.9**	**0.9-1.0**
Parrot	***mshEdgeRGB_T1***					
	mshEdgeRGB_T2					
Apple	***mshEdgeRGB_T1***					
	mshEdgeRGB_T2					
	mshEdgeRGB_T1					

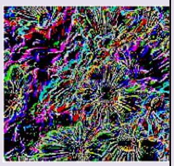
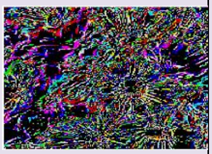
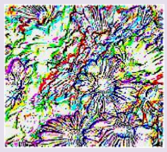
Flower	***mshEdgeRGB_T2***					

Fig.2 Comparative Analysis of edges detected using ***mshEdgeRGB_T1*** and ***mshEdgeRGB_T2*** Algorithms for different Membership ranges

Table 1 Evaluation Metrics for Varying Membership Values
(*mshEdgeRGB_T1* and ***mshEdgeRGB_T2*)**

Sr. No.	**Image Name**	**Membership Value**	***mshEdgeRGB_T1***				***mshEdgeRGB_T2***			
			Edge Pixels	**PSNR Value**	**MSE Value**	**L2RAT Value**	**Edge Pixels**	**PSNR Value**	**MSE Value**	**L2RAT Value**
1	**Parrot**	0.5-0.9	64292	9.384	7492.03	2.685	28451	12.104	4005.28	1.215
		0.6-0.9	63554	9.334	7579.72	2.671	27971	12.038	4066.44	1.206
		0.7-0.9	60703	9.140	7925.98	2.598	26702	11.842	4254.72	1.174
		0.8-0.9	52071	8.963	8255.46	2.303	24571	11.598	4500.27	1.102
		0.9-1.0	230502	2.291	38363.40	11.71	266347	1.745	43503.01	13.764
2	**Apple**	0.5-0.9	36565	8.903	8369.43	2.257	19257	10.754	5464.99	1.248
		0.6-0.9	36196	8.849	8474.04	2.246	19142	10.724	5503.40	1.245
		0.7-0.9	34199	8.658	8856.30	2.168	18510	10.570	5701.30	1.220
		0.8-0.9	27021	8.564	9049.38	1.800	16998	10.359	5985.51	1.142
		0.9-1.0	115148	2.475	36776.28	8.863	132456	1.958	41425.70	10.375
3	**Flower**	0.5-0.9	57632	6.464	14676.63	1.453	39457	7.034	12870.50	1.084
		0.6-0.9	56586	6.343	15091.53	1.440	38935	6.960	13094.20	1.077
		0.7-0.9	51586	5.924	16619.99	1.356	37340	6.743	13764.50	1.051
		0.8-0.9	35457	5.409	18713.22	0.999	33352	6.360	15032.02	0.962
		0.9-1.0	52160	4.458	23295.74	1.741	70339	3.828	26930.50	2.369

4. Conclusion

In visual image processing, edge detection is an important technique used to identify various parameters within images. It shows discontinuities in color images, which occur due to sudden changes in pixel values, color intensity and noise, helping to define image boundaries. This paper shows a comparative analysis of two algorithms, ***mshEdgeRGB_T1*** and ***mshEdgeRGB_T2***, for detecting edges in RGB images. Both algorithms utilize Mamdani Fuzzy Inference Systems and fuzzy inference rules, examining edge pixels across various membership values and ranges. The results indicate that ***mshEdgeRGB_T1*** is more effective at detecting edge pixels under certain membership values, while ***mshEdgeRGB_T2*** gives sharp edges at some membership values. Additionally, the comparison between edge images obtained from these algorithms and the Prewitt operator shows differences in PSNR, MSE and L2RAT values, highlighting the experimental results among the methods. Future research will further compare these techniques with other edge detection methods, such as Sobel, Canny, and Roberts operators.

Declaration of Competing Interest: The authors have not revealed any conflicts of interest related to this work.

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