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A Novel Approach of Satellite Image Enhancement Using DWT Based on 2-Type Fuzzy Logic

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Abstract: This study proposes a new approach to enhance the dark and low-contrast satellite images captured under poor illumination. Images are converted from RGB to HSV color space in order to separate the Hue (H), Saturation (S), and luminance (V) components. Enhancement is achieved in saturation and luminance components using Discrete Wavelet Transform (DWT) and 2-type fuzzy logic. DWT breaks the images into high and low-frequency sub-bands and results in approximation and detailed coefficients. The approximation coefficient consists of low-frequency components, which are further modified using the 2-type Fuzzy Logic technique. Fuzzy logic is basically a point operation-based technique based on the fact that human perceived brightness characteristic is not linear. Inverse Wavelet Transform is used to achieve the enhanced saturation components. The luminance component (V) is passed through class-limited adaptive histogram equalization. All the enhanced components are then combined to get the enhanced image and finally reconverted to RGB color space. The proposed scheme significantly works well for enhancing and sharpening dark and low-contrast satellite images. The experimental results obtained by the proposed method show improved performance in terms of PSNR, MSE, mean, and variance.

Keywords: DWT, CLAHE, 2-Type Fuzzy Logic

Introduction

Visual information works from a human perspective because the human brain processes images much faster than any other type of data. Visual information processing is a vision that directs action. An image is a very good source of information since it contains maximum information in comparison to another type of information. However, the analysis of images is not possible all time due to various reasons. Therefore processing an image to make it for analysis purposes is one of the most important steps in image analysis. One of the important steps in image processing is image enhancement. Is an elementary and important step in image processing. Image enhancement improves the interpretability of information in images in various fields such as military, medical image analysis, inspection, astronomy, satellite imaging, and many other applications (Bhandari *et al.*, 2016). In general, raw satellite images are dark and low-contrast images due to poor illumination, visualization, equipment, and noise. Hence miscellaneous kinds of artifacts and noise contaminate the images and degrade their quality (Bhandari *et al.*, 2016; 2014). So, contrast enhancement and noise removal algorithms are needed to extract accurate information and process the data. One thing that is kept in mind in all these techniques is to remove the noise while preserving brightness and edge information. In general satellite images have a very low range of brightness values because of insufficient lighting (Bhandari *et al.*, 2014). Although there are many causes of image degradation noise is the main degradation factor of satellite imaging. As a result, images are required to be processed through some enhancement methods.

These methods are broadly classified into two categories one is the spatial domain and the other is the frequency domain. Spatial domain methods are based on the direct manipulation of pixels in an image. There have been several techniques in a spatial domain such as

Generalised Histogram Equalization (GHE) (Kumar *et al*., 2012), high pass filtering, low pass filtering, gamma correction, Singular Value Decomposition (SVD), etc., In frequency domain techniques, images are first transformed into the frequency domain to analyze spectrums. After spectrum analysis, the inverse transform is applied to reconstruct the image. Fourier Transform (FT), Discrete Cosine Transform (DCT), Wavelet Transform (WT), Short Time Fourier Transform (STFT), etc., are some examples of frequency domain techniques used to analyze images. Several researchers have used DCT for spectral separation and singular frequency component analysis because of its feasibility in enhancing features (Weeks *et al*., 1999). However, there are a few inadequacies in converting remote senses satellite images using DCT algorithms (Bhandari *et al*., 2014). These limitations are removed by utilizing DWT for contrast enhancement in recent years. WT basically separates the high and low-frequency components and consequently gives four sub-bands named as Low-Low (LL), High-Low (HL), Low-High (LH), and High-High (HH). The basic information resides in the LL band and the high frequency bands contain the edge information. Many techniques have been proposed using DWT to separate the noise components from the original data. Bhandari *et al*. (2014) presented a method in which, contrast enhancement is done for low-resolution remote sensing images. Here authors have used DWT-SVD and the Cuckoo Search (CS) based hybrid algorithm. An algorithm using Discrete DWT and Class Limited Adaptive Histogram Equalization (CLAHE) has also been proposed by Rajakullayappa *et al.* (2017). CLAHE is basically an adaption of histogram equalization in contrast limited way. It splits the original image into a number of blocks of equal size and then each block analyzes by contrast-limited histogram equalization (Rajakullayappa *et al*., 2017). In this study, an improved approach is used for contrast enhancement of dark and low-resolution remote sensing satellite images. The given approach is based on an adaptive manner using DWT-Fuzzy logic and the CLAHE technique. The approach given in this study provides better results by applying the fuzzy logic algorithm which is based on point operation. Recently The RGB color image is converted to HSV color space as some earlier works have also shown that the performance of HSV color space is good in color improvement (Naik and Murthy, 2003). Here, Hue (H) which is an important factor for an image as it can generate color-shifting problems, has kept constant. On the other hand, other factors such as; luminance (V) and Saturation (S) or only L components are modified. The designed method's results are compared with the performance of previous methods such as; CIE LUV color space and CIE Lab color space from the comparative analysis, it is found that controlling the H component is easier than controlling other parameters also and avoiding change in colors in the HSV color space significantly. As a result, in this study, a new H stabilizing algorithm is developed, based on a mapping function to improve the S components and CLAHE for L components. The mapping function includes the Wavelet Transform followed by the fuzzy logic technique. The wavelet analysis-based image enhancement technique decomposes the input image in its four frequency sub-bands. Most of the information exists in low frequencies so we omit other high-frequency bands and apply the fuzzy logic algorithm in the LL band. The LL band has illumination information which is further modified by the pixel operation in order to improve the contrast. Then IDWT is performed on this fuzzified image along with the other high-frequency sub-bands (LH, HL, HH) in order to obtain the edge information of the image. Lastly, the image is converted back to RGB color space using HUE (H), modified Saturation (S), and modified luminance (V) components. To identify the performance of the proposed technique, different quantity parameters are used.

Overview of DWT, 2-Type Fuzzy Logic and CLAHE

The discrete wavelet transform has been quite a popular research area in recent years in the field of image processing. Wavelet transforms are faster, more adaptive, and provide better compression. The basic idea behind the wavelet transform is to decompose a signal in its detailed and approximation coefficients up to desired level. The main advantage of WT is that it gives more accurate and efficient results in comparison to Fast Fourier Transform (FFT) and DCT.

Discrete Wavelet Transform

The DWT decomposes any given data into a set of basic frequencies band. One of the major advantages of wavelet transform is its ability to perform MRA i.e., Multi-Resolution Analysis. MRA is basically a technique of storing and processing the image in multiple processes (Gonzalez *et al*., 2010). Wavelet transforms are also effective with signals having sharp peaks and values unlike Fourier transform (Gonzalez *et al*., 2010; Verma *et al*., 2021). Basically, wavelet transform is a tool that divides information or a given function into different frequency components and allows one to study each component separately with a resolution matched to its scale. DWT decomposes the signal into a mutually orthogonal set of wavelets (Verma *et al*., 2021) using the property of dilation and translation. DWT uses a mother wavelet to process the information.

The selection of wavelet function is an important point different work has been reported for image processing using different wavelets. A pair of filters having a finite impulse response such as low pass and high pass filters is used to divide the frequency into different bands. This process is repeated recursively till we get the frequency band of the given input image as per our requirement. To process an image 2-dimensional DWT is used, which decomposes an input image, where 1-D WT is firstly applied along the rows, and then the resultant images are decomposed along the columns (Verma *et al*., 2021). Therefore, the row image is converted into four frequency bands; these frequency bands have low and high frequencies. We can further divide these bands for further multiple scaling purposes. With the help of wavelet coefficients calculation, we can analyze the image (Verma *et al*., 2021; Ashish *et al*., 2011). This can be done by the inner product between input data and the wavelet function. The coefficients of DWT can be calculated by the equations given below:

$$W_{\ell}(j,k) = \sum\nolimits_m W_{\ell}(m,k-1)h(m-2j) \tag{1}$$

$$W_h(j,k) = \sum\nolimits_m W_{\ell}(m,j-1)g(m-2j) \tag{2}$$

where, $W_{\ell}(x, y)$ represents the x^{th} scaling coefficient at the y^{th} level and $W_h(p, q)$ represents the x^{th} wavelet coefficient at *the* y^{th} level. However, $h(n)$ and $g(n)$ indicate the low pass and high pass filter which gives dilation coefficients. The obtained coefficients are corresponding to scaling and wavelet functions respectively.

After analysis, the original data is recovered using Inverse Discrete Wavelet Transform (IDWT). This is the exact reverse process of DWT. In this case, the obtained wavelet coefficients are firstly up-sampled by factor 2 and then a set of low pass and high pass filters are applied to up-sampled data. In accordance with the complimentary IDWT is given as:

$$W_{\ell}(j,k) = \sum\nolimits_n W_{\ell}(n,k+1)h'(j-2n) + \sum\nolimits_l W_h(l,k+1)g'(j-2l) \tag{3}$$

where, $h'(n)$ and $g'(n)$ signifies the low-pass and high-pass filters corresponding to the mother wavelet respectively.

Fuzzy Logic

The concept of fuzzy set theory was introduced by Zadeh (1972; 1965). In this case, an array is considered by utilizing an image. Here, an image with the size of = $M \times N$ is considered along with gray levels, which have size L. As an array of fuzzy singletons, each having a value of membership function which denotes its degree of brightness relative to some brightness level l with l = 0, 1, .., L-1 (Ensafi and Tizhoosh, 2005; Tizhoosh and Fochem, 1995). For I (image) I, we can use Eq. 4 where g_{mn} represents the intensity of pixel of mn^{th} position and μ_{mn} its membership value:

$$I = \bigcup_m^M \bigcup_n^N \frac{\mu_{mn}}{g_{mn}} \tag{4}$$

where, m = 1, 2, 3, ..., M and n = 1, 2, 3, ..., N. The membership function is basically a curve that defines a mapping function between each point in the input space and tells a degree of membership between 0 and 1 (Pal, 1992). In other words, it characterizes a suitable property of an image such as darkness, textural property, etc. The membership value for each grey level is calculated as:

$$\mu(g_{mn}) = \frac{g_{mn} - g_{min}}{g_{max} - g_{min}} \tag{5}$$

where, g_{max} and g_{min} are the maximum and minimum gray level values of the image respectively. For measuring new gray levels, the following transformation can be utilized:

$$g'_{mn} = \frac{L-1}{e^{-1}-1} \times (e^{-\mu(g_{mn})\beta} - 1) \tag{6}$$

where, parameter β is a fuzzifier and L is the desired number of gray levels.

Generally, histogram manipulations are point operations (Toet, 1992) so a transformation function is required to enhance the contrast value of individual pixels. A function f transforms the gray level g_{mn} of an original image into the g'_{mn} of the enhanced image (Zadeh, 1965). The transformation function is defined as follows:

$$g'_{mn} = \lambda \times f(\mu(g_{mn})) \tag{7}$$

To determine the parameter λ and the function f, some conditions must be fulfilled:

f = must be nonlinear (e.g., logarithmic)
λ = should map the new gray values into [0, L-1]. In other words:

$$g'_{mn} = \Big|_{\mu(g_{mn})=0} = 0 \tag{8}$$

$$g'_{mn} = \Big|_{\mu(g_{mn})=1} = L-1 \tag{9}$$

To meet these demands, f and λ can be defined as follows:

$$\lambda = L-1 \cdot \left(\frac{1}{e^{-1}-1}\right) \tag{10}$$

$$f(\mu(g_{mn})) = e^{-\mu}(g_{mn})^{\beta} - 1 \tag{11}$$

So, the final equation can be written as:

$$g'_{mn} = (L-1) \cdot \left(\frac{1}{e^{-1}-1}\right) \cdot \left(e^{-\mu}(g_{mn})^{\beta} - 1\right) \tag{12}$$

The fuzzifier β modifies and hence improves the membership values and hence the gray level dynamics of the resulting image can be changed (Pal and King, 1983; Zimmermann, 2011; Kumar *et al*., 2021; Verma *et al*., 2021).

Contrast Enhancement of Luminance Component

This study uses a contrast enhancement technique also known as CLAHE. In this technique, the enhancement of the V component is done in the HSV color space. Here, the clip-limit is used to enhance the V component and the value of the clip-limit is 0.01 used. In this way, the V component image is split into 8×8 tiles. After this, the histogram is used by utilizing uniform distribution for tiles of images. The mathematical relation of the modified gray levels for the standard CLAHE method with Uniform Distribution can be written as:

$$g = (g_{max} - g_{min}) \times P(f) + g_{min} \tag{13}$$

where, g_{max} and g_{min} are the maximum and minimum gray values of images respectively. $P(f)$ is the cumulative probability distribution.

Methods

In this study, a new method is given for the enhancement of remote sensing satellite images. The study is included mainly in three parts. In the first one, the color space conversion is included. The RGB color space is converted into HSV color space as HSV color space is good for color improvement. The second part is to apply the DWT on the Saturation (S) part. DWT decomposes the image into approximation and detailed coefficients. Most of the information is concentrated in the approximation coefficient i.e. LL band and the edges are concentrated in other sub-bands (i.e., LH, HL, and HH). Therefore, separating the edge information presents in high-frequency components and applying illumination enhancement using a 2-type fuzzy logic histogram hyperbolization technique in the LL band will protect the edge information from possible degradation. The enhanced S component is reconstructed by using IDWT. CLAHE is applied to the luminance (V) component. The enhanced image is obtained using HSV to RGB conversion using enhanced S, enhanced V, and the preserved H component. The final Image (satellite image) is enhanced significantly with respect to illumination. The final image also becomes sharper, which makes further easy analysis. The steps of the proposed algorithm are given in the flowchart (Fig. 1) and explained:

Step 1: The first step of the proposed algorithm is data acquisition. Here, in this study, a dark and low-contrast multispectral satellite image is obtained for image processing and analysis. The darkness of the image is also measured by measuring the mean value. The mean value of the image is very low, which indicates darker intensity regions

Step 2: RGB color-spaced image is converted to HSV color space

Step 3: After the HSV conversion, Hue (H) component is preserved so that no losses occur in color information

Step 4: The input image S component is processed first by passing wavelet's 1-level decomposer for contrast enhancement which gives four frequency sub-bands i.e., LL, HL, LH, and HH

Step 5: Then after, getting DWT components, fuzzy logic point operation is applied on the low-frequency component (LL band) individual pixel in order to modify them which gives us LL_{new}

Step 6: After getting LL_{new}, apply IDWT using LL_{new}, LH, HL, and HH in order to get the edge information which gives enhanced saturation (S_{new}) component

Step 7: Luminance (V) component is processed through class-limited adaptive histogram equalization which gives an enhanced luminance component (V_{new})

Step 8: The image is converted back to RGB color space using H, S_{new}, and V_{new} components

Step 9: In the final step, an improved, enhanced, and sharper multispectral image is achieved, which does not contain a blurring effect and contains all useful information

Step 10: This step includes the calculation of different parameters for examining the performance of a given method. Here, variance, mean, MSE, and PSNR parameters are used for performance analysis

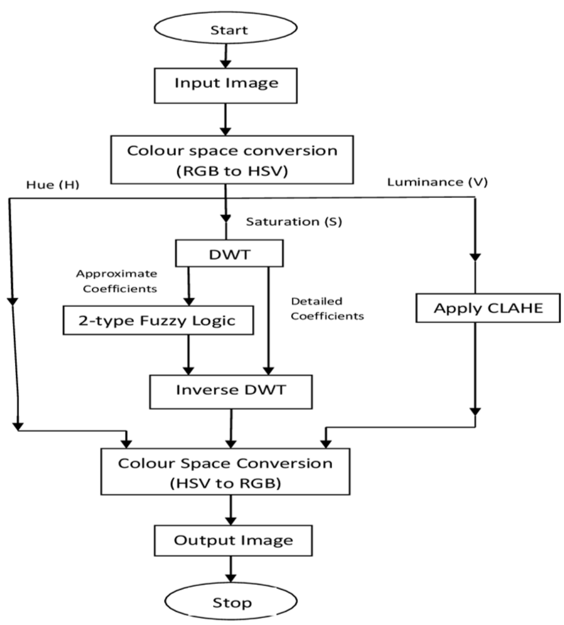

Fig. 1: Flow chart of a projected algorithm

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Results and Discussion

Remote sensing satellite images often suffer from poor illumination, resulting in a limited range of intensity values. As a result, contrast enhancement is frequently utilized to improve the image's brightness and sharpness. This issue is particularly prevalent in multiband satellite images, where contrast enhancement is essential for proper interpretation and visualization. A variety of methods have been employed for this purpose and this study compares three techniques: DWT-SVD, DFT-SVD, and DWT-SVD based on type-1 fuzzy logic. The effectiveness of the proposed methods is validated using a range of dark satellite images. Figure 2 depicts the images processed through the proposed algorithm (DWT-FHH and CLAHE). To begin, low-contrast satellite images are transformed from RGB to HSV color space, and the saturation component of the HSV image is processed through DWT. DWT breaks down the image into four frequency sub-bands: LL, LH, HL, and HH. The LL sub-band is further processed through fuzzy logic and then IDWT is performed to extract edge information from high frequency bands. The hue component is preserved throughout the process to maintain color information. CLAHE is subsequently applied to the luminance component of the HSV image to enhance the luminance. The enhanced components are then combined to obtain the final enhanced image in the HSV domain, which is subsequently converted back to the RGB color space. The final enhanced image is shown in Fig. 3.

For the experimental results, different quantitative performance measures are used to compare different image enhancement algorithms. In this section, the performance of DWT-SVD, DCT-SVD, and DWT-SVD based on the Fuzzy Logic technique and the proposed DWT based on 2-type fuzzy logic is estimated on the bases of the fidelity of the reconstructed image to the original image. Here, the measured parameters are; mean, variance, PSNR, Absolute Mean Brightness Error (AMBE), and MSE parameters are considered. Different dark and low-brightness satellite images are used to demonstrate the result of this algorithm:

(1) AAMBE: it measures the difference between the average intensity level of the original image and the average intensity level enhanced image and can be calculated as:

$$AMBE = \left|E(y) - E(x)\right. \quad (14)$$

where, $E(x)$ and $E(y)$ is the average intensity level of the original image and enhanced image, respectively.

(2) Mean (μ): This indicates the average value of all intensity of an image. It indicates the average brightness of an image. If I (x, y) denotes the intensity of the image of size $P \times Q$ then it is given as:

$$Mean\,(\mu) = \frac{1}{PQ}\sum_{x=1}^{P-1}\sum_{y=1}^{Q-1} I(x,y) \quad (15)$$

where, $I\,(x, y)$ denotes the intensity of the image of size $P \times Q$:

(1) Variance is the square of the deviation of the intensities from the mean:

$$Variance = \frac{1}{PQ}\sum_{x=1}^{P-1}\sum_{y=1}^{Q-1}\left(I(x,y) - \mu\right)^2 \quad (16)$$

Here $I(x, y)$ is the intensity of the image of size $P \times$ Q.

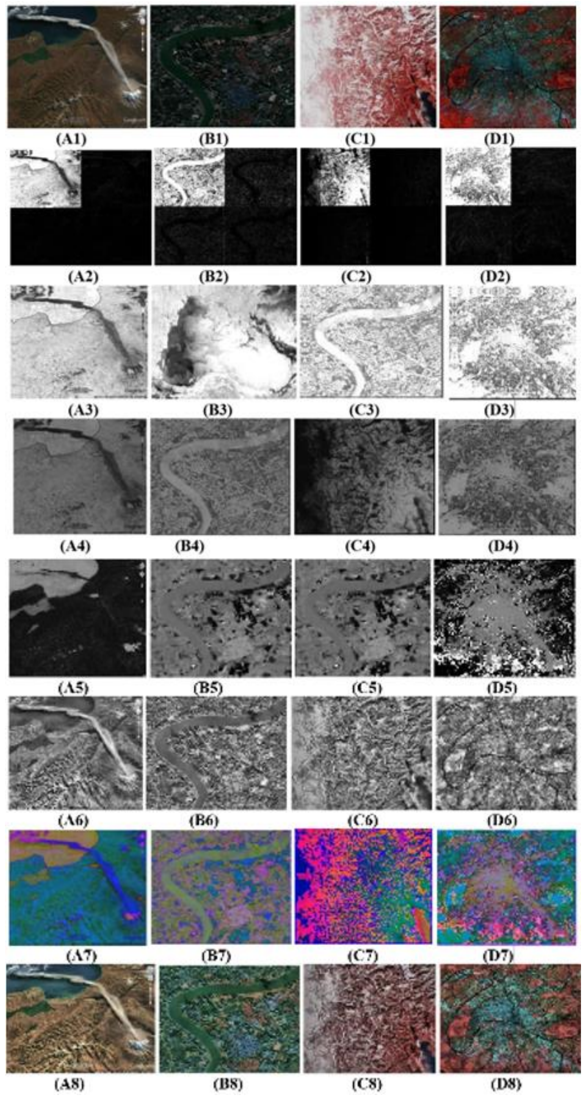

Fig. 2: (A1-D1) low contrast remote sensing satellite images, (A2-D2) decomposition of saturation component using DWT, (A3-D3) Fuzzy logic algorithm on LL part of image, (A4-D4) IDWT of the new LL image, (A5-D5) preserved hue component of original image, (A6-D6) CLAHE performed on the luminance component of original image, (A7-D7) enhanced HSV image, (A8-D8) enhanced RGB output image

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(2) Mean Square Error (MSE) measures the average square of error between original and enhanced mages. It gives the error matrix between the two. A higher value of *MSE* signifies a higher error and a lower value of *MSE* represents a lower error. It is defined as:

$$MSE = \frac{\sum_{P,Q}\left[I_1(x,y) - I_2(x,y)\right]^2}{PQ} \tag{17}$$

where, I_1 and I_2 are the original image enhanced image, respectively and the size of both images is of $P \times Q$.

(3) *PSNR* is a quality measurement between original and enhanced images. It computes the ratio between the maximum power of a signal and the power of corrupting. The High *PSNR* signifies the better quality of the enhanced image. *PSNR* is calculated using the following equation:

$$PSNR = 10log_{10}\frac{R^2}{MSE} \tag{18}$$

where,
R = The maximum possible pixel value of the input image
$PSNR$ = The calculated in *db*

The proposed algorithm is performed over 4 different dark and low-contrast satellite images. Different parameters are calculated and are summarized in Table 1. To show the superiority of the proposed technique PSNR and *MSE* values are compared using different techniques which are given in Table 2.

The graph is plotted based on the values of different methods in order to show the effectiveness of the proposed method over conventional contrast and brightness image enhancement techniques. A comparison of *MSE* and *PSNR* values of different methods is plotted and shown in Figs. 4-5 respectively.

Fig. 3: Comparison of the input image and enhanced image

Table 1: Table showing different parameters using the proposed technique (DWT-2-type fuzzy logic)

	Input image		Output image					
S. No.	Mean (μ)	Variance (σ)	Mean (μ)	Variance (σ)	MSE (β)	PSNR (α)	AMBE	Maximum error
1.	0.2169	0.0161	0.3715	0.0315	0.0336	77.5967	1.4992e-07	0.5985
2.	0.2921	0.0227	0.3774	0.0341	0.0162	83.9383	1.2180e-08	0.5185
3.	0.1156	0.0143	0.2981	0.0250	0.0426	75.5437	1.0589e-06	0.5022
4.	0.2066	0.0238	0.3219	0.0313	0.0239	80.5656	6.1680e-07	0.4253

Table 2: Comparison of results between input, DCT-SVD, DWT-SVD, and DWT-SVD using FHE and proposed DWT-2-type fuzzy logic

	Input image		Output DCT-SVD		Output DWT-SVD		Output DWT-SVD-FHE fuzzy logic histogram equalization)		Output of proposed WT-2-type fuzzy logic	
S. No.	Mean (μ)	Variance (σ)	PSNR (α)	MSE (β)	PSNR (α)	MSE (β)	PSNR (α)	MSE (β)	PSNR (α)	MSE (β)
1.	0.2169	0.0161	α=42.2362	β=3.8856	α=43.9727	β=2.6050	α=54.2174	β=0.2482	α=77.5967	β=0.0336
2.	0.3521	0.0443	α=43.98017	β=2.6006	α=45.6989	β=1.7506	α=54.6476	β=0.2248	α=83.9383	β=0.0162
3.	0.5733	0.0564	α=42.9643	β=3.2859	α=40.4032	β=5.9260	α=55.3021	β=0.1933	α=75.5437	β=0.0426
4.	0.2066	0.0238	α=43.0583	β=3.2155	α=40.3139	β=6.0490	α=62.9045	β=0.0335	α=80.5656	β=0.0239

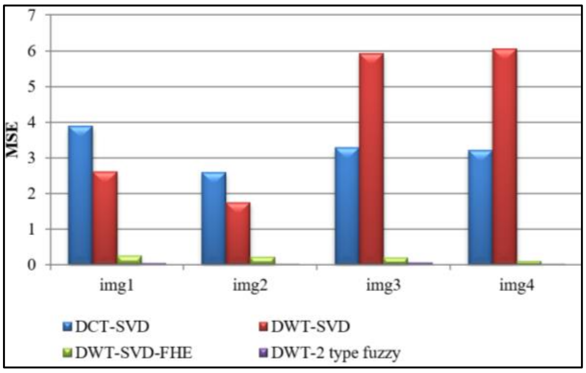

Fig. 4: Graph showing a comparison of MSEs on different images using different techniques

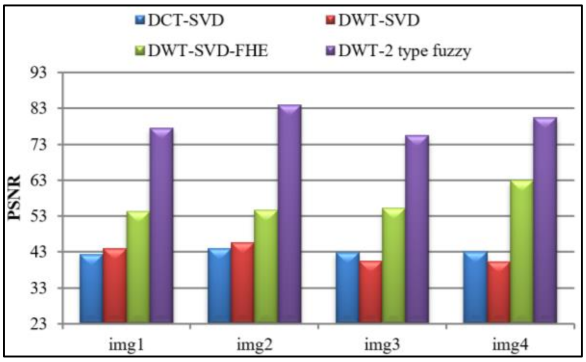

Fig. 5: Graph showing a comparison of PSNR values on different images using different techniques

Conclusion

This study proposes a satellite image contrast and brightness enhancement technique based on DWT-2 type Fuzzy Logic and followed by Class Limited Adaptive Histogram Equalization (CLAHE). The image is converted in HSV color space and different algorithms are performed over the saturation and luminance components. The hue component of the image is preserved so that color information does not lose. The proposed technique uses DWT to split an image into lower and higher frequency sub-bands of the saturation component. Then 2- a type fuzzy logic algorithm is performed over the low-frequency part of the image in order to improve illumination information. Then inverse DWT is performed over new LL, LH, HL, and HH sub-bands. After that, the luminance component of the image is passed through the CLAHE process which improves the sharpness of the image. The image is converted back into RGB color space. Histogram and other required intensification parameters are calculated and obtained enhanced HSV image is converted back into RGB color space.

The performance of the proposed algorithm is tested on the dataset (various satellite images). The evaluation is done using various parameters such as; mean-variance, PSNR, AMBE, and MSE along with visual results (images). These results very clearly show that the proposed technique superior to various conventional techniques.

Future Scope

The future scope of the proposed approach of satellite image enhancement using DWT based on 2-type fuzzy logic offers exciting opportunities for further advancements in the field of remote sensing and image processing. By exploring different fuzzy logic techniques, hybrid approaches, specific applications, optimization, and integration with advanced technologies, the proposed approach can potentially contribute to the development of more effective and efficient satellite image enhancement methods for various remote sensing applications.

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Author's Contributions

Surjeet Singh Patel and Pratibha Verma: Literature reviewed work.

Vivek Kumar Tamta and Abhilekh Bartwal: Implementation work.

Banit Negi, Abhishek Gupta and Pushkar Praveen: Paper written work.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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