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Fuzzy transform for high-resolution satellite images compression

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ABSTRACT

Many compression methods have been developed until now, especially for very high-resolution satellites images, which, due to the massive information contained in them, need compression for a more efficient storage and transmission. This paper modifies Perfilieva's Fuzzy transform using pseudo-exponential function to compress very high-resolution satellite images. We found that very high-resolution satellite images can be compressed by F-transform with pseudo-exponential function as the membership function. The compressed images have good quality as shown by the PSNR values ranging around 59-66 dB. However, the process is quite time-consuming with average 187.1954 seconds needed to compress one image. These compressed images qualities are better than the standard compression methods such as CCSDS and Wavelet method, but still inferior regarding time consumption.

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1. INTRODUCTION

Satellite images, especially images with very high-resolution, have massive information contained in them. Very high-resolution satellite images has a lot of nonzero high-frequency components while the bandwidth and the storage to transmit and store them is not unlimited [1, 2]. Those constraints make it necessary to develop compression methods for satellite images. On 1998, [3] modified the standard JPEG coding to increase the compression ratio for satellite images. Since then, researches on compression for satellite images has been conducted [4-7]. The consultative committee for space data systems (CCSDS) also developed several recommended standards to image compression for remote sensing images such as CCSDS 121.0-B-2 [8] and CCSDS 122.0-B-2 [9]. Although CCSDS is the recommended standard, this method still have room for improvement,as shown in [10, 11].

The CCSDS method and many other compression methods commonly use discrete wavelet transform (DWT), a transformation method based on Mallat's decomposition of multi-resolution signal first introduced in 1989 [12]. DWT in compression works by representing signals as components that appear at different scales [13]. In 2006, [14] introduced a transformation method with fuzzy approximation, called Fuzzy transform (F-transform). F-transform is a fuzzy-based function that transform a real interval $[a,b]$ into n-dimensional matrix. Several applications of this method includes statistics such as forecasting [15] and robust estimators [16], and image processing such as restoration [17] and compression [18]. In 2008, [19] provides a F-transform based compression on natural greyscale images.

In this paper, we modify the F-transform by changing the membership function using pseudo-exponential function and apply the method to compress very high-resolution images taken from Pleiades satellite. We evaluate the results based on the peak signal-to-noise ratio (PSNR) value and the time consumption. A comparison with the recommended standard CCSDS and Wavelet method is also provided in order to observe whether our proposed method is better than the original F-transform and the recommended standard method or not.

The paper is organized in the following way. Section 2 describes the fuzzy transform theory as the background for this research. Section 3 describes our proposed method, which is fuzzy transform with modified membership functions. The dataset for this research and our research method is described in section 4. Section 5 shows the experimental results with statistical analysis and comparison with existing methods. The conclusions and future works presented in section 6.

2. FUZZY TRANSFORM

Fuzzy transform, or F-transform, is a method of transformation introduced by [14]. Fuzzy transform combines the concept of classic transformation methods, such as Fourier transform, with the concept of conditional (IF-THEN) rules found in fuzzy modelling. In general, F-transform established a correspondence between real, continuous functions and n-dimensional real vectors. F-transform enables us to solve complicated mathematical problems by simplifying them into n-dimensional matrices, and solving them using simple linear algebra before transforming the solutions back into the problems' original domain.

2.1. Membership Functions

Membership functions are the basis of F-transform. F-transform works by creating fuzzy subsets of the domain using several predetermined memberships functions. Then, average values of a function over the fuzzy subsets are calculated, so that the function could be mapped from the fuzzy subsets to the average function values [14]. There are many functions that could be used as a membership function, such as triangular function [20], trapezoid function [21], and gauss function [22]. Common function used for F-transform's membership function is sinusoidal function [19, 23]. The (1) shows the formal expression for sinusoidal membership functions $A_1(x), A_k(x), A_n(x)$ when $k = 2, \ldots, n-1$.

$$A_1(x) = \begin{cases} 0.5(\cos\frac{\pi}{h}(x - x_1) + 1) & \text{for } x \in [x_1, x_2] \\ 0 & \text{for otherwise} \end{cases} \tag{1}$$

$$A_k(x) = \begin{cases} 0.5(\cos\frac{\pi}{h}(x - x_k) + 1) & \text{for } x \in [x_{k-1}, x_{k+1}] \\ 0 & \text{for otherwise} \end{cases}$$

$$A_n(x) = \begin{cases} 0.5(\cos\frac{\pi}{h}(x - x_n) + 1) & \text{for } x \in [x_{n-1}, x_n] \\ 0 & \text{for otherwise} \end{cases}$$

2.2. Direct and Inverse F-transform

F-transform establishes a correspondence between a set of continuous functions on interval *[a,b]* and a set of n-dimensional vectors. Supposed $A_1, \ldots, A_n$ are memberships functions used to create fuzzy subsets from domain *[a,b]*, and f is any function from the set of continuous functions on interval *[a,b]*. The n-tuple of real numbers $[F_1, \ldots, F_n]$ given by (2). is the F-transform of f with respect to $A_1, \ldots, A_n$ [14].

$$F_k = \frac{\int_a^b f(x)A_k(x)dx}{\int_a^b A_k(x)dx}, k = 1, \ldots, n \tag{2}$$

This paper uses the slightly modified F-transform by [19] to make it compatible with image compression, namely discrete, two-variable F-transform with definition as follow: Supposed R is a grey image of N x M pixels. The normalized value of the pixel, denoted $R(i,j)$, can be seen as fuzzy relation $R:(i,j) \in [1, \ldots, N] \times [1, \ldots, M] \rightarrow [0,1]$. The compression of R is done by discrete F-transform with two variables $[F_{kl}]$ given by:

$$F_{kl} = \frac{\sum_{j=1}^{M}\sum_{i=1}^{N} R(i,j)A_k(i)B_l(j)}{\sum_{j=1}^{M}\sum_{i=1}^{N} A_k(i)B_l(j)} \tag{3}$$

where $A_1, \ldots, A_n$ denotes memberships functions used to create fuzzy subsets from domain *[1,N]*, while B denotes memberships functions used to create fuzzy subsets from domain *[1,M]*. Matrix F_{kl} created by (3). can be transformed back into the original domain using inverse F-transform expressed as follow:

$$R^F_{n(B)m(B)}(i,j) = \sum_{k=1}^{n(B)} \sum_{l=1}^{m(B)} F^B_{kl} A_k(i) B_l(j) \tag{4}$$

where $R^F_{n(B)m(B)}$ approximates the original block R_B [19].

3. PROPOSED METHOD

This paper use pseudo-exponential function [24] instead of sinusoidal function as membership function for the F-transform. Pseudo-exponential function is a bell-shaped function defined by its center value m and a value k<1. As the value k increases, growth rate also increases, making the bell more narrow. The function's formal expression can be seen in (5).

$$P(x) = \frac{1}{1+k(x-m)^2} \tag{5}$$

An illustration for pseudo-exponential function with $m = 5$ and $k = 0.5$ is shown in Figure 1.

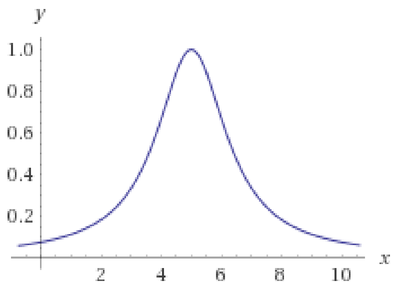

Figure 1. Sample graph of pseudo-exponential function with $m = 5$ and $k = 0.5$

We use F-transform with pseudo-exponential function as the membership functions to compress very high-resolution satellite images. The (6) shows the formal expression for pseudo-exponential function membership functions $A_1(x), A_k(x), A_n(x)$ when $k = 2, \ldots, n-1$.

$$A_1(x) = \begin{cases} \dfrac{1}{1+2.5\left(x-\frac{(x_1-h/2)+(x_2-h/2)}{2}\right)^2} & \text{for } x \in [x_1, x_2] \\ 0 & \text{for otherwise} \end{cases} \tag{6}$$

$$A_k(x) = \begin{cases} \dfrac{1}{1+0.9\left(x-\frac{x_{k-1}+x_{k+1}}{2}\right)^2} & \text{for } x \in [x_{k-1}, x_{k+1}] \\ 0 & \text{for otherwise} \end{cases}$$

$$A_n(x) = \begin{cases} \dfrac{1}{1+2.5\left(x-\frac{(x_{n-1}+h/2)+(x_n+h/2)}{2}\right)^2} & \text{for } x \in [x_{n-1}, x_n] \\ 0 & \text{for otherwise} \end{cases}$$

Value $k = 2.5$, $k = 0.9$, as well as values for m are chosen from several trials and errors so that the functions $A_1, \ldots, A_n$ follows the properties of membership functions as defined in [14].

4. RESEARCH METHOD

We use F-transform with pseudo-exponential function as the membership functions to compress very high-resolution satellite images. The experiment is conducted in the following way. First we breakdown the images into 8 x 8 tiles and normalize the pixel's values of each tile into *[0,1]* interval. Each interval is then transformed using F-transform equation into n-dimensional matrices. The matrices are then reconstructed into new, compressed images using inverse F-transform. For comparison, we also conduct compression using several methods, which are the original F-transform with sinusoidal membership function [14], CCSDS method [25], and Wavelet method (https://github.com/gpeyre/matlab-toolboxes). The results are then evaluated by their Peak Signal-to-Noise Ratio (PSNR) value and time consumption.

PSNR is a method commonly used for evaluating image and video processing [1, 19]. As the name implies, PSNR is a ratio between the maximum value of a signal and a noise disturbing the signal representation, calculated using mean squared error (MSE). The lower the noise and thus the MSE value, the higher the PSNR value and the image quality [26]. The equation for PSNR is as followed [27]:

$$\mathrm{PSNR} = 20 \times \log_{10} \frac{Q^2}{\frac{1}{N}\sum_{i=1}^{N-1} u^2(i,j)} \tag{7}$$

where Q is the possible maximum value of the pixel, N is the number of pixels of the image, and u is the value of pixel.

The dataset used in this paper is very high-resolution images, that are images with spatial resolution under one meter, taken from Pleiades constellation satellites. Pleiades satellites produce multispectral images which consist of four bands: red, green, blue, and near infrared. For the experiment, we use natural color combination (red, green, blue) with 0.5m spatial resolution stored in 16-bit. Figure 2 shows several samples of the dataset.

(a) (b) (c)

(d) (e) (f)

Figure 2. Sample images from pleiades satellite, each image is 512×512 pixel

5. RESULTS AND ANALYSIS

The compression results under F-transform method with pseudo-exponential and sinusoidal membership functions, CCSDS method, and Wavelet method are presented in Table 1 and Table 2. Comparison for the PSNR value is presented in Figure 3. It can be seen that for every compression ratio we tested, the PSNR values of compressed images by F-transform, both using pseudo-exponential and sinusoidal function are significantly higher that those of CSDS method and Wavelet method. The PSNR value for the proposed method is 19.83% higher that the compressed images using the recommended standard CCSDS, and 50.76% higher than Wavelet method. The proposed method's PSNR value is only 2.07% lower than PSNR value of F-transform with sinusoidal membership function. As higher PSNR value means more similarity between original image and compressed image, the results show that images compressed with the proposed method are able to retain more information and thus better than ones compressed with the recommended standard CCSDS and Wavelet method, while only slightly inferior to F-transform with sinusoidal membership function. The comparison of visual quality of the compressed images is show in Figure 4.

In term of time consumption, the proposed method has highest complexity with average time needed to compress one image 187.1954 seconds. The second highest complexity goes to F-transform with sinusoidal membership with average consumption time 92.0505 seconds, followed by Wavelet method with average consumption time 77.5427 seconds. Finally, CCSDS has lowest complexity with average time consumption only 5.9484 seconds. Comparison for the time consumption for each method is presented in Figure 5. The time needed to compress one image is 103.36% longer than F-transform with sinusoidal membership function, 141.41% longer than Wavelet method, and 3000.99% longer than CCSDS method.

Table 1. PSNR value comparison

Image	Proposed method	FTR Sinusoidal	CCSDS	Wavelet
a	64.2247	65.5262	49.7598	38.9216
b	61.1088	62.3283	51.6546	41.2769
c	60.0716	61.3048	51.3007	40.9539
d	62.0266	63.3734	52.1096	41.3733
e	61.8383	63.1893	52.0226	41.547
f	59.1535	60.4292	50.9664	41.0264
g	59.6043	60.8858	51.1199	41.0346
h	59.8889	61.2527	51.1134	40.8848
i	62.4584	63.7471	52.4634	41.743
j	61.2233	62.5091	51.4339	41.0603
k	61.3578	62.6257	51.811	41.3317
l	61.3429	62.6158	48.4503	37.8963
m	65.7913	67.175	54.1632	42.5295
n	61.1833	62.514	51.915	41.3975
o	61.4205	62.7444	51.439	40.7937
p	61.6772	62.979	49.7393	39.1772
Average	61.52321	62.82499	51.34138	40.80923

Table 2. Time consumption comparison

Image	Proposed method	FTR Sinusoidal	CCSDS	Wavelet
a	212.9517	154.9033	58.1557	99.1191
b	184.7287	89.2543	5.7312	81.7483
c	184.7486	87.2382	2.5049	80.7124
d	186.2446	89.077	2.4185	74.019
e	186.7833	88.3517	2.9738	74.8206
f	183.9899	88.3534	2.3871	80.4487
g	186.6846	87.9148	2.0391	79.8415
h	186.1348	87.5532	1.9005	79.497
i	183.9322	88.1632	1.8178	73.5511
j	185.1347	88.352	2.2433	77.3702
k	185.6652	87.2715	1.7092	76.1796
l	187.3381	86.7543	1.4685	77.0895
m	184.8607	86.7985	3.4427	57.1168
n	184.9699	88.0559	2.3741	75.3593
o	184.6126	87.0047	2.2246	75.4597
p	186.3473	87.7614	1.7841	78.3506
Average	187.195431	92.05046	5.948444	77.54271

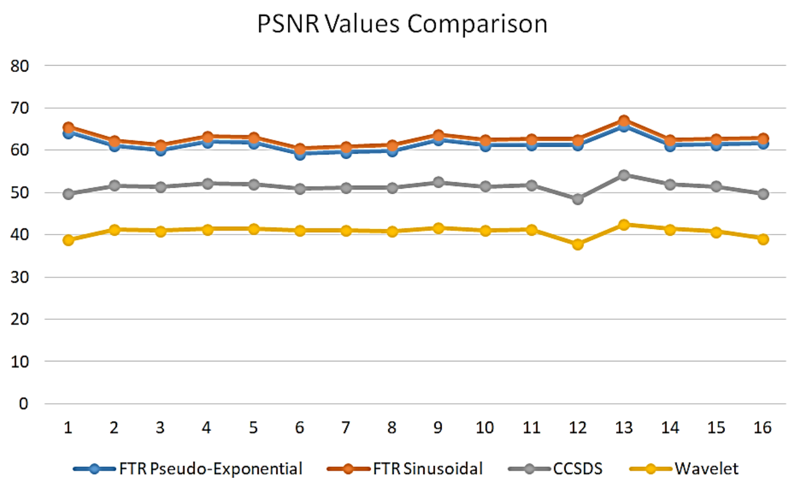

Figure 3. Comparison of PSNR values

Original image

Proposed method

FTR Sinusoidal

CCSDS

Wavelet

Figure 4. Visual comparison between F-transform, Wavelet, and CCSDS method

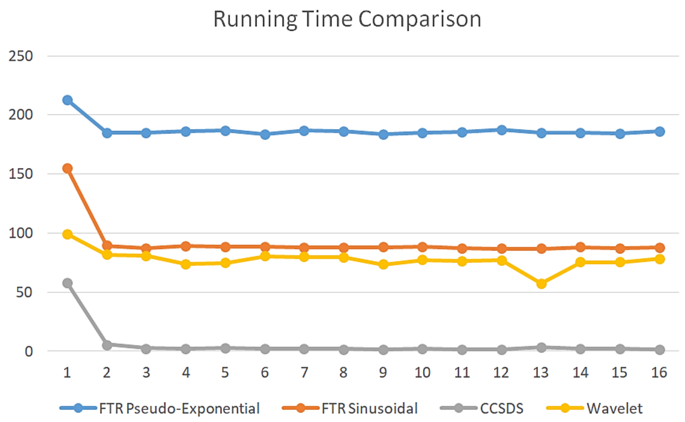

Figure 5. Comparison of time consumption

The main cause for the proposed method's costly time consumption is the preprocessing that happened before the actual compressing. As explained in Section 2, before applying F-transform to the image, we first breakdown the image into 8×8-pixel tiles and normalize the pixel's value into *[0,1]* interval. After transformation, we denormalize the pixel's value and merge the tiles back into single image. This additional process also add the time consumption.

6. CONCLUSION

From the experimental results, we conclude that very high-resolution satellite images can be compressed by F-transform with pseudo-exponential function as the membership function. The compressed images have visually good quality, and could retain most of the information as shown by the PSNR values which ranging around 59-66 dB. This result is better than the recommended standard CCSDS and Wavelet method. The proposed method's PSNR value is only slightly inferior to PSNR value of F-transform with sinusoidal membership function. However, the proposed method is still inferior in regard to time consumption. The time needed to compress one image is much longer than F-transform with sinusoidal membership function, the Wavelet method, and the CCSDS method. For the future works, we will attempt to lessen the time consumption needed to image compression by lowering the complexity of the coding and experimenting other membership functions.

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