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Development of mathematical frame work to remove herringbone artifact in brain MRI images and assessment of image quality after artifact removal

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Abstract: Frequently the MRI technique is susceptible to artifacts which may be system hardware/software related or patient related. The herringbone artifact is hardware related artifact which appears as a fabric of herringbone or stripe in either frequency encoding or phase encoding direction throughout the brain image or on a limited number of rows or columns of arbitrary width in an image. The presence of this artifact in brain MRI images will reduce the diagnostic quality or confuse the pathology. During image analysis, the artifact will affect the segmentation accuracy and classification of abnormality such as lesion or tumor. In this paper, a mathematical framework is developed and implemented using FFT and Canny edge detector to remove the herringbone artifact. The artifact removed image is restored using inverse FFT. The method is developed in frequency domain which preserves the image details and sharpness of edge information. The image quality is assessed by finding signal-to-noise ratio and energy loss before and after artifact removal.
Keywords: MRI image, Herringbone artifact, FFT, Canny edge detector, Filter, Signal-to-noise ratio, Energy loss.

I. INTRODUCTION

Magnetic resonance imaging (MRI) is an imaging technique that uses a strong and uniform magnetic field and radio frequency pulses to create the complete images of the brain and its surrounding tissues. However, the technology of MRI is associated with many potential sources of artifacts which can degrade the diagnostic quality of an image or simulate the pathology [1]. The herringbone artifact is one such artifact which is related to MRI system hardware. There are three reasons for this artifact to occur during image acquisition using MRI scanner. They are

Electromagnetic spikes caused by gradient coils
Fluctuations in power supply and
RF pulse discrepancy

The radiologist alone cannot remove this artifact immediately during image acquisition. The possible solution to remove this artifact can be done by the technician or service engineer of the MRI scanner. However the artifact can be removed in technical ways by developing image processing techniques [2][3][4].

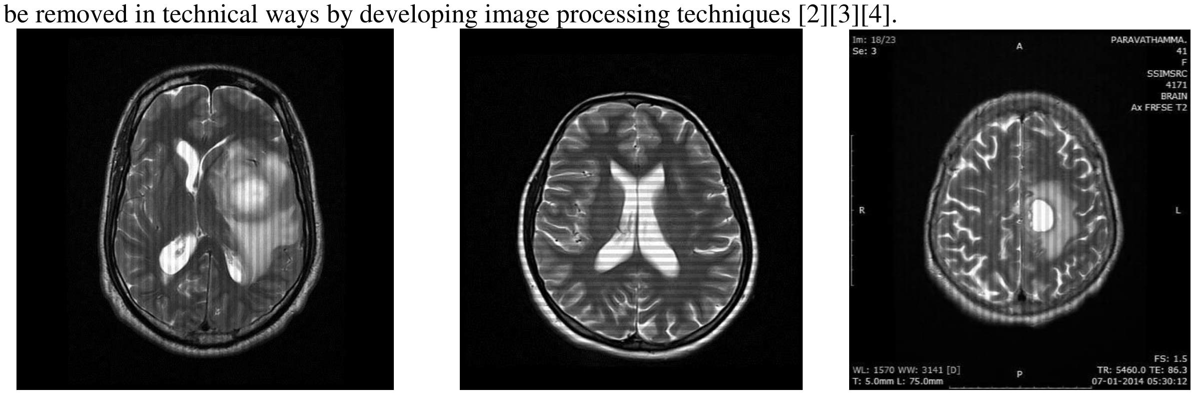

Figure 1 Herringbone artifact brain MRI images

In figure 1, the herringbone artifact appears in the form of a fabric of herringbone or stripe in vertical or horizontal direction on the image. This artifact will be represented by a mathematical model and algorithm can be developed using image processing techniques to remove the artifact. There is no published work found in the literature to remove herringbone artifact in brain MRI images. There are usually two ways to reduce the noise or artifact in images. One is the spatial domain processing and other is the frequency domain processing. The frequency domain is a better choice for preserving image details and edger sharpness [5]. In this paper we develop and implement a novel technique in the frequency domain to remove herringbone artifact in brain MRI images. The concept of this technique is based on the removal of stripe artifact on satellite images found in [6]-[8].

II. METHODOLOGY

The herringbone artifact in brain MRI image can be represented in general form as [8]

$$f(r,c) = x(r,c) + n(r,c) \tag{1}$$

Where $f(r,c) =$ Artifact image
$x(r,c) =$ Prior image (without artifact)
$n(r,c) =$ Noise artifact
$r = 0,1,2, \dots\dots\dots . \mathrm{M}-1$ rows and
$c = 0,1,2, \dots\dots\dots . \mathrm{N}-1$ columns of discrete image matrix of size MxN

The artifact is considered to be in the form of vertical or horizontal stripes occurring in the frequency or phase encoding direction of brain MRI image. The herringbone artifact in the image $f(r,c)$ is defined as a constant offset value 'A' of arbitrary width 'w' spreads over the entire image or only over a limited part of rows or columns[9][10]. It can be mathematically represented as

$$n(r,c) = \begin{cases} A & \forall\, (r,c) \in w \\ 0 & otherwise \end{cases} \tag{2}$$

Where n(r,c) represents the herringbone artifact of offset pixel intensity value 'A' along rows or columns of width 'w' in the image.
The herringbone artifact can be quantified for a given image sample by knowing the pixel values of artifact image and artifact removed image

2.1. Fourier Transform-

Suppose the spatial domain image represented as $f(r,c)$ with $r = 0,1,2, \dots\dots\dots . \mathrm{M}-1$ rows and $c = 0,1,2, \dots\dots\dots . \mathrm{N}-1$ columns specifies the raw image of size M x N. The two-dimensional Fourier Transform denoted as $F(u,v)$ which can be obtained from the mathematical expression [11]

$$F(u,v) = \sum_{r=0}^{M-1}\sum_{c=0}^{N-1} f(r,c)\, e^{-j\omega\left(\frac{ur}{M}+\frac{vc}{N}\right)} \tag{3}$$

For all $u = 0,1,2, \dots\dots\dots . \mathrm{M}-1$,and $v = 0,1,2, \dots\dots\dots . \mathrm{N}-1$

Where $F(u,v)$ represents the Fourier transform spectrum and the frequency variables are u and v. This domain is comparable with the spatial domain (the coordinate system defined by the spatial variables r and c). The rectangular M × N area defined by $u = 0,1,2, \dots\dots\dots . \mathrm{M}-1$, and $v = 0,1,2, \dots\dots\dots . \mathrm{N}-1$ can be considered as a rectangular frequency. Clearly the rectangular frequency has the same size as that of the input spatial image f(r,c).

2.2. Inverse Fourier Transform-

The Inverse Fourier transform of the image is obtained from equation [11]

$$f(r,c) = \frac{1}{MxN}\sum_{u=0}^{M-1}\sum_{v=0}^{N-1} F(u,v)\, e^{j\omega\left(\frac{ur}{M}+\frac{vc}{N}\right)} \tag{4}$$

For all $r = 0,1,2, \dots\dots\dots . \mathrm{M}-1$ rows and $c = 0,1,2, \dots\dots\dots . \mathrm{N}-1$ columns

The values in equation (3) are also called the Fourier series coefficients. The value of the Fourier transform in the center of the rectangular frequency $F(0,0)$ is called dc component of Fourier transform which represents the complete image detail [11].

2.3. Canny Edge detector-

The Canny edge detector is based on the first derivative coupled with noise cleaning. The detection of abrupt changes of the frequencies in the frequency spectrum is influenced by the presence of artifact. Hence the smoothing of these frequencies improves the detection of 'bright spots'. The Canny edge detector tries to achieve an optimal trade-off between the two by approximating the first order derivative of the Gaussian. The Gaussian function for 1-D is given by the equation (5).

$$G = \frac{1}{\sqrt{2\pi\sigma}} e^{-\left(\frac{x^2}{2\sigma^2}\right)} \quad (5)$$

Gaussian first order derivative is used to calculate the gradient in horizontal and vertical direction. Figure 2 shows the Gaussian function in 1-D and its first order derivative. Sigma value is used to set the width of the Gaussian function. Canny edge detector performs better than Sobel or Prewitt edge detectors and provides a good detection, localization and uni-response to a true edge [12].

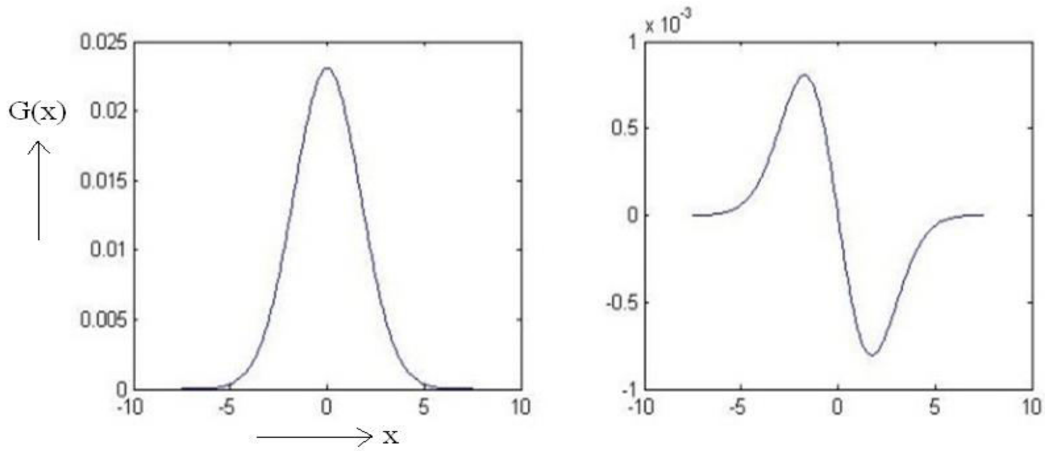

Figure 2 Gaussian functions and its first order derivative.

In the frequency domain, we apply Fourier Transform to convert a spatial domain image into frequency domain to obtain frequency spectrum of the image. The image detail is concentrated at the origin of image spectrum and the frequency components due to herringbone artifact appear as bright spots in the Fourier spectrum F(u,v) which can be detected using any edge detection algorithm. A filter H(u,v) is created using Canny edge detector and applied on the image spectrum to remove the artifact frequency components present [14] in the frequency spectrum of the image that are created by herringbone artifact. The final image $f'(r,c)$ is restored using inverse FFT [6]. Since convolution in the spatial domain is equivalent to multiplication in the frequency domain, we obtain a processed image as given by [6]

$$F'(u,v) = F(u,v) * H(u,v) \quad (7)$$

$$f'(r,c) = \text{IFFT}(F'(u,v)) \quad (8)$$

Where F(u,v) = Fourier transform of artifact image

H(u,v) = Filter transfer function

$F'(u,v)$ = Fourier transform of filtered image

$f'(r,c)$ = Artifact removed image

The Algorithmic steps for removal of herringbone artifact is given below

Read the Herringbone artifact brain MRI image f(r,c) from the database

Apply FFT using equation (3) to obtain frequency spectrum F(u,v)

Calculate the sigma value using equation (9) and use it to set appropriate threshold value for Canny edge detector

$$\sigma = \sqrt{\frac{\sum_{u,v}[F(u,v) - F_{mean}]^2}{MxN}} \quad (9)$$

where,

$$F(u,v) = \sum_{r=0}^{M-1} \sum_{c=0}^{N-1} f(r,c)\, e^{-j\omega\left(\frac{ur}{M}+\frac{vc}{N}\right)}$$

$$F_{mean} = \frac{1}{MxN} \sum_{u,v} F(u,v)$$

for all $u = 0,1,2, \dots \dots \dots .M - 1$, and $v = 0,1,2, \dots \dots \dots .N - 1$.
Apply Canny edge detector on Fourier transform image F(u,v)
Retain the image details concentrated at the origin of the image spectrum.
Filter $H(u, v)$ is created by complementing the resulted image generated from the Canny edge detector
Perform multiplication of $F(u, v)_* H(u, v)$ and then apply Inverse FFT using equation (4) to restore the image.

2.4. Assessment of image quality-
After successful removal of herringbone artifact in brain MRI images using FFT and Canny edge detector algorithm, it is necessary to assess the image quality by qualitative and quantitative analysis. The qualitative analysis deserves that the processed image must be free from artifact, but all other details of the image and edge information must be well-preserved. The quantitative assessment requires that the local mean values of the processed images away from herringbone artifact need to be retained which is an important requisite for quantitative analysis of the image [9][11][13].
The well-known qualitative method in signal processing is the signal-to-noise ratio (SNR) for images which is specified by equation (10)

$$SNR = 10\log_{10}\left(\frac{\text{Signal Power}}{\text{Noise Power}}\right) \quad (10)$$

The signal power is defined by equation (11) for input image

$$\text{Signal Power} = \sum_{r=0}^{M-1}\sum_{c=0}^{N-1} f(r,c)_2 \quad (11)$$

And noise power is defined by equation (12) for processed image

$$\text{Noise Power} = \frac{1}{MxN}\sum_{r=0}^{M-1}\sum_{c=0}^{N-1}[f(r,c) - f'(r,c)]^2 \quad (12)$$

Where M and N are rows and columns of discrete image matrix. Original image is $f(r,c)$ and processed image is $f'(r,c)$. Equation (12) is also called as Mean Square Error (MSE).
In quantitative assessment, the total energy of an image signal is decisive. The loss of energy in the image signal after artifact removal is represented as the difference between the energy of original image signal $f(r,c)$ and the filtered image signal $f'(r,c)$ relative to the original image, which results in the relative energy loss expressed in percentage as given by [11]

$$\text{Energy loss (\%)} = \frac{\sum[f(r,c) - f'(r,c)]^2}{\sum f(r,c)^2} \text{x100} \quad (13)$$

III. RESULTS AND DISCUSSION

The algorithm is implemented using MATLAB tool and tested for the brain MRI images shown in figure 1 which shows the presence of herringbone artifact appearing as stripes in either frequency encoding or phase encoding directions. These images are processed by the algorithm and the resulted images are shown in figure 3. It is found that the herringbone artifact is removed.

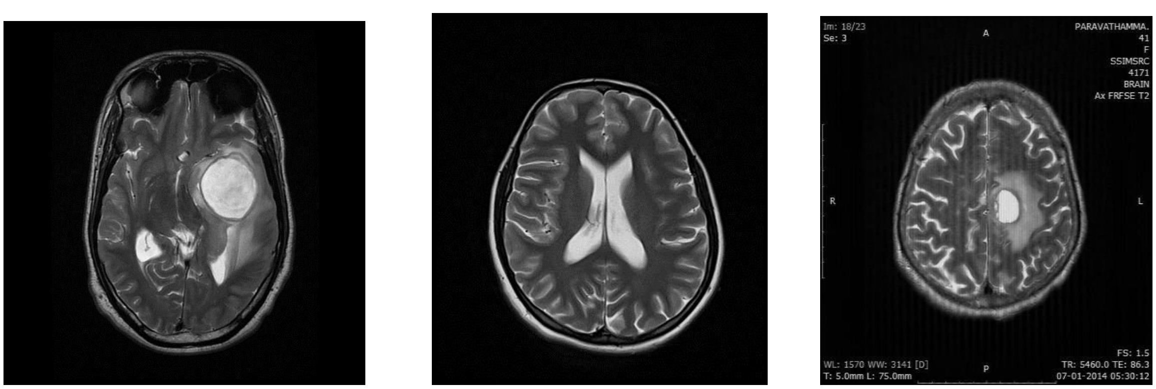

Figure 3 Restored brain MRI images after herringbone artifact removal

The detailed results of the various steps of the proposed algorithm are shown in figure 4 for one sample image. The figure 4(a) represents the input image with herringbone artifact in the form of stripes in the vertical direction. The figure 4(b) is the frequency spectrum which shows the complete image details concentrated at the origin of the spectrum and artifact components as bright spots at different frequencies. The figure 4(c) shows the detected artifact components as bright spots using Canny edge detector. The figure 4(d) shows the filter spectrum constructed by complementing the Canny edge detector result. The figure 4(e) is the multiplication of 4(b) with 4(d) which shows the artifact components to appear as dark spots. The inverse Fourier transform is applied to reconstruct the image shown in figure 4(f) which is free from artifact.

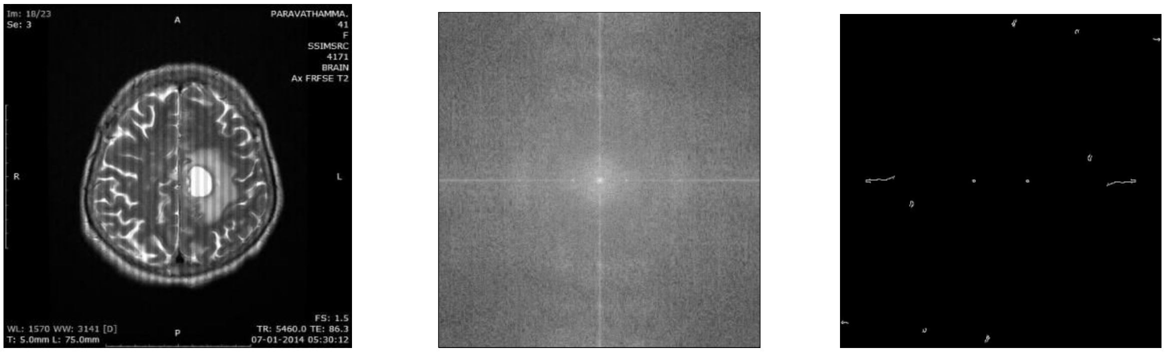

Figure 4.(a)Artifact image (b) Frequency spectrum of (a) (c) Canny edge detector result

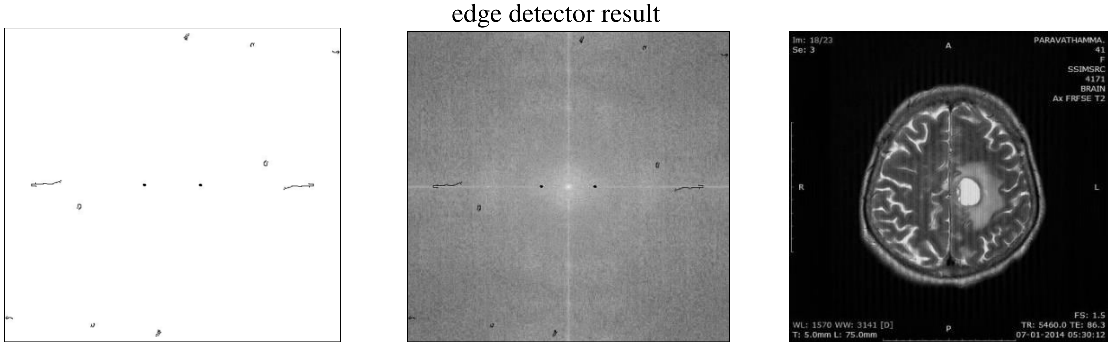

Figure 4. (d) Complemented result of (c) (e) Multiplication of (b) and (d) (f) Restored image

Figure 4 (a)-(f) Results of algorithm implementation steps for one image sample of figure 3

The image quality after artifact removal is verified by finding the signal-to- noise ratio and energy loss metrics. The table 1 shows the values of Signal-to-noise ratio and Energy loss for sample images. The results clarify the effectiveness of the proposed algorithm/technique in removing the herringbone artifact with increased Signal-to-noise ratio and negligible energy loss after artifact removal.

Table 1 Signal-to-Noise Ratio (SNR) and Energy Content for brain MRI images

Image Samples	SNR in dB		Energy Content		
	Before artifact removal	After artifact removal	Energy before artifact removal	Energy after artifact removal	Energy loss in % after artifact removal
1	81.4731	90.6513	2.5647	2.5622	0.0968
2	78.7854	86.9348	2.4532	2.4530	0.0079
3	67.1836	89.1378	2.6451	2.6449	0.0081
4	73.7259	84.4315	2.5391	2.5389	0.0082
5	79.2784	86.9317	2.6231	2.6226	0.0176
6	79.0932	92.6239	2.9132	2.9105	0.0943
7	71.3394	87.9418	2.8541	2.8536	0.0168

IV. CONCLUSION

The herringbone artifact in brain MRI images is represented mathematically and processed using the proposed algorithm. From the above results, it is found that the proposed algorithm for removal of herringbone artifact in brain MRI images using FFT and Canny edge detector is a powerful approach in frequency domain. It is designed for wide range of herringbone or stripe artifact removal in brain MRI images. The proposed algorithm is implemented on MATLAB platform and tested on various herringbone artifact brain MRI Images taken from the established data base of the present work. The images are analyzed both qualitatively and quantitatively using signal to noise ratio and energy loss metrics. The table 1 shows values of signal-to-noise ratio and energy loss for few image samples.

It is observed that there is a greater improvement in SNR of processed image with minimal loss of energy. The frequency domain technique preserves all the image details. The experimental results suggests that the proposed algorithm is efficient and suitable to remove herringbone artifact which occurs in either frequency encoding or phase encoding direction(horizontal or vertical direction) on brain MRI Images.

V. REFERENCE

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