Using Markov constraint and constrained least square filter to develop a novel method of passive terahertz image restoration

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Abstract. In recent years, passive terahertz imaging has gained significant attention in both research and practice. One big challenge with passive terahertz imaging is its low-quality images with high level of noise. State-of-the art image restoration methods have been developed for image denoising, such as methods based on Markov constraint and regular filter methods. Building upon these two methods, this paper develops a novel method for passive terahertz image restoration which preserves well both high frequency and low frequency information of the images. Performance of our method is evaluated using two common image criteria of the image sharpness, i.e. edge intensity and definition. Experimental results showed our method outperform state-of-the art methods for passive terahertz image restoration.

1. Introduction
Passive terahertz imaging is a newly introduced technology that shows good potential in security check field and has drawn much attention in research in recent years [1-3]. One of the major advantages of passive terahertz imaging is its good transmission capability, which can be used to detect dangerous objects concealed in personnel’s clothes. Moreover, terahertz wave is radiation free to human body, which meets the safety concern of security screening [4-5].

Although passive terahertz imaging permits many advantages over traditional security check technology, its’ application in real-world scenarios suffers from its relatively low noise ratio image. Marcin Kowalski et al. adopted threshold to image de-noising and contrasted various edge detection methods [6-7]. Dai etc. put forward a terahertz image average denoising method using suitable level Gaussian noise and adaptive color block-matching 3D filtering. Their method improved the visual effect and removed interference [8]. However, it lacks an appropriate image restoration method for terahertz security check images.

In this study, we developed a novel method based on Markov random field theory to improve passive terahertz imaging quality. In the following sections, we will report our method in detail. In particularly, in section 2, we will describe the image capture and pre-process. In section 3, we will present our method of passive terahertz image restoration based on Markov Random Field theory. Lastly, we will conclude our study findings and algorithm performance.
2. Pre-processing of passive terahertz image
Passive terahertz imaging mainly relies on detecting the thermal radiation of targets and backgrounds. In this study, we used a terahertz point detector, a terahertz scanner, and terahertz lenses to capture the image. The terahertz scanner was composed of flapping mirror and trihedral mirror. The trihedral mirror was used for vertical scanning. Each surface of trihedral mirror was ellipsoid. During each rotation of the trihedral mirror, the detector captured three lines of the imaging target. The horizontal scanning was completed with the flapping mirror. Then the terahertz signal entered the terahertz detector and was converted to electronic signal. After processed by a computer program, a passive terahertz image was generated.

![Original image](image1.jpg) ![Pre-processed image](image2.jpg)

Figure 1. Passive Terahertz image and pre-processed image

The original image is shown in Figure 1 (a). It is quite blurred with the influence of diffraction limit of the imaging system. There are a lot of radiation noises of background, random noises from detector and electromagnetic noise from the scanning device. To solve the problem of original terahertz images, it is necessary to pre-process the images. A filter in frequency domain and adaptive median filter is adopted to remove the noises. After the de-noising processing, linear contrast stretch is used to enhance the image. The result image is shown in Figure 1 (b).

3. Passive terahertz image restoration
According to Fourier optics, optical imaging system is considered as a low-pass filter. The goal of this step is to recover a high-quality image \( f(x,y) \) from its degraded observation \( g(x,y) \).

\[
g(x,y) = f(x,y) * h + n
\]

In equation (1), \( g \) is a degraded image, and \( f \) represents the high-quality idea image. \( h \) is point spread function (PSF), a known degradation matrix and \( n \) is additive noise. \( g \) can be treated as an ideal image influenced by optical transfer function \( H \) and additive noises \( n \).

3.1. Terahertz image restoration based on Markov constraint
The grayscale of pixel in passive terahertz images is only influenced by its nearby pixels, and this matches with the characteristic of the Markov random field. We considered image model follow Poisson distribution and then we applied Markov constraint to the image model. Equation (2) shows the iteration process.
\[ f_{n+1}^\hat{} = f_n^\hat{} \exp \left\{ \left( \frac{g_{ij}}{(f_n^\hat{} * h_{ij})} - 1 \right) \oplus h_{ij} - \alpha \frac{\partial}{\partial f} U(f_n^\hat{}) \right\} \]

(2)

\( h \) is the PSF of imaging system. \( n \) is the number of iterations. \( U(f) \) is called energy function, and in this study, we chose to use Geman model. Equation (3) shows the complete \( U(f) \) function. \( \alpha \) is regularization parameter, which used to balance the weight of the Markov constraint. In doing so, we can achieve good results of preserving the objects’ edge in the image.

\[ U(f) = \sum_c \frac{(D_c(F) / \gamma)^2}{1 + (D_c(F) / \gamma)^2} \]

(3)

In equation (3), \( c \) is the associated clique. We defined \( c \) using the 2nd neighborhood system in this study. \( D_c(F) \) is the difference of the image. The algorithm has good capability to extrapolate the frequency spectrum of images, but it will damage the low frequency information of the images.

3.2. Improved Terahertz image restoration method using Markov constraint and constrained least square filter

To address the shortcomings of the image restoration based on Markov constraint, we adopted a regular filter to improve the image quality.

Regular filter is also called constrained least square filter, whose core idea is to find an estimation of original image \( \hat{f} \) to minimum Euclidean norm of noise \( ||\hat{f} - Hf|| \). It is described in frequency domain as follow:

\[ \hat{F}(u,v) = \left[ \frac{H^*(u,v)}{[H(u,v)]^2 + \gamma|P(u,v)|^2} \right] G(u,v) \]

(4)

\( \hat{F} \) and \( G \) are the frequency spectrum of estimated and degraded images respectively. \( \gamma \) is Lagrange coefficient, and \( P(u,v) \) is Laplacian operator. The regular filter algorithm permits good retaining of the low frequency information despite of the poor ability to extrapolate the frequency spectrum of images. The low frequency information of regular filter and the high frequency information of the original method are combined in this improved method.

3.3. Experimental Results

In this section, we compared restored images using the above mentioned three different methods, namely original Terahertz image restoration based on Markov constraint, regular filter Terahertz image restoration, and the improved Terahertz image restoration method using Markov constraint and constrained least square filter. In particularly, we attained both restored images and their according low-pass filtered images to highlights the characteristics of each method.

The resulting image restoration using different methods are shown in Figure 2. In particularly,

- The left image of Figure 2 (a) is the regular filter restoration image and the right image of Figure 2 (a) is its spectrum image.
- The left image of Figure 2 (b) is the low–pass filtering image of the left image of Figure 2 (a) and right image of Figure 2 (b) is its spectrum image.
- The left image of Figure 2(c) is the restored image using original Terahertz image restoration based on Markov constraint and the right image of Figure 2(c) is its spectrum image.
Figure 2. Results of different image restoration algorithm

(a) Image restored by regular filter and its frequency spectrum
(b) The result image of (a) low-pass filtered and its frequency spectrum
(c) Image restored by MAP restoration based on Markov constraint and its frequency spectrum
(d) The result image of (c) low-pass filtered and its frequency spectrum
(e) Image processed by algorithm in this article and its frequency spectrum
• The left image of Figure 2(d) is the low–pass filtering image of the left image of Figure 2 (c) and right image of Figure 2 (d) is its spectrum image.

• The left image of figure 2(e) is the restored image using improved Terahertz image restoration using Markov constraint and constrained least square filter, and the right image of figure 2(e) is its spectrum image.

The images clearly showed that the original method has good capability of preserving the high frequency information of the images. However, the regular filtering method has good capability of preserving the low frequency information of the images. By combing both the original method and the regular filtering method, the improved method did show good capability of preserving both high frequency and low frequency information.

3.4. Experimental Results
Edge intensity (CV) and image definition (Definition) are adopted to evaluate the quality of terahertz restoration images using the three above methods. Equation (5) and (6) show the formula:

\[ CV = \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} |f \cdot \text{La}| \]

\[ \text{Definition} = \sum_{i=1}^{N_1-1} \sum_{j=1}^{N_2-1} \frac{[f(i+1,j)-f(i,j)]^2 + [f(i,j+1)-f(i,j)]^2}{N_1 \times N_2} \]

\( f \) is the image needs to be evaluated, La is a Laplacian operator, \( N_1 \times N_2 \) is the size of the image. CV and Definition are both used to describe the sharpness of the images. The degree of the image quality is determined by the value of both of the CV and Definition. The results of image quality evaluation are shown in Table 1.

|                | Regular filter | Original method | Improved method |
|----------------|----------------|-----------------|-----------------|
| CV             | 0.0387         | 0.0402          | 0.0414          |
| Definition     | 0.0548         | 0.0602          | 0.0639          |

4. Conclusion
In this study, we presented a novel method for the quality restoration of terahertz images with noises. This method exploits the disadvantage of original image restoration based on Markov constraint and the advantage of regular filter image restoration method. By combining these two methods, the improved terahertz image restoration method preserves good high frequency and low frequency information of the images. Thus, the resulting images achieve good quality.

The performance of our method was evaluated on two important image quality criteria, edge intensity and definition. Results showed the improved method has the highest CV and definition value among the three methods. Therefore, the experimental results demonstrate good performance, i.e. shaper, of our method in terms of terahertz image restoration.

Acknowledgments
Supported by the National Natural Science Foundation of China (61875140) and Beijing Natural Science Foundation (4181001).

References
[1] Chan W L, Deibel J A and Mittleman D M 2007 Imaging with terahertz radiation *Reports on Progress in Physics* **70**(8) pp 1325-1379
[2] Sun Q, He Y, Liu K, Fan S, Parrott E P and Pickwell-MacPherson E 2017 Recent advances in
terahertz technology for biomedical applications Quantitative imaging in medicine and surgery 7(3) 345

[3] Mittleman D M 2018 Twenty years of terahertz imaging [Invited] Optics Express 26(8) pp 9417-9431

[4] Federici J F, Schukin B, Huang F, Gary D E, Barat R, Oliveira F and Zimdars D 2005 THz imaging and sensing for security applications—explosives, weapons and drugs. Semiconductor Science and Technology 20(7)

[5] Morozov D, Doyle S M, Banerjee A, Brien T L, Hemakumara D, Thayne I G, Hadfield R H and et al 2018 Design and characterisation of titanium nitride subarrays of kinetic inductance detectors for passive terahertz imaging Journal of Low Temperature Physics 193(3-4) pp 196-202

[6] Kowalski M, Piszczek M, Palka N and Szustakowski M 2012 October Improvement of passive THz camera images. In Millimetre Wave and Terahertz Sensors and Technology V (Vol 8544 p 85440N) International Society for Optics and Photonics

[7] Kowalski M, Kastek M, Walczakowski M, Palka N and Szustakowski M 2015 Passive imaging of concealed objects in terahertz and long-wavelength infrared Applied Optics 54(13) pp 3826-3833

[8] Dai L, Zhang Y, Li Y and Wang H 2014 MMW and THz images denoising based on adaptive CBM3D International Conference On Digital Image Processing