

Research on the Improvement Method for Default Image Display Effect of Dual-Energy X-Ray Security Inspection Equipment Based on Improved NL-Means Filter

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Abstract

Aiming at the shortcomings of uneven image color and prominent noise in the default image display effect of existing dual-energy X-ray security inspection equipment, the corresponding improvement method is studied. Firstly, the improved Non-Local Means filter (hereinafter referred to as improved NL-Means) is used to perform adaptive smoothing on the original high and low-energy images to obtain the corresponding material characteristic images. Furthermore, the improved NL-Means filter is used again to smooth the material characteristic images, so as to improve the phenomena of uneven image color and prominent noise points. However, this filtering method has a serious problem of low real-time efficiency, making it difficult to apply in engineering. This paper studies three acceleration methods. The first one is to selectively implement the improved NL-Means filter from the perspective of the image itself; the second one is to reasonably reduce the number of structural operations based on the principle and structure of the algorithm; the third one is to convert the floating-point exponential operation into a look-up table operation from the perspective of engineering practice. The experimental results show that the proposed method effectively improves the default image display effect of the security inspection equipment, which plays a very positive role not only in the security inspectors' interpretation of images but also in improving the performance indicators of the equipment.

Keywords

NL-Means Filter, Acceleration, Dual-Energy X-Ray, Security Inspection

1. Introduction

Traditional X-ray security inspection equipment displays colors based on the inspection of item materials. Therefore, the visual quality of the final color images displayed by this type of equipment is the focus of competition among various security inspection equipment manufacturers. Our goals are low noise, uniform color, and outstanding extreme indicators.

The data processing process for the default image display effect of existing dual-energy X-ray security inspection equipment consists of two parts. One part is to obtain the material information of the corresponding image using the original high and low-energy images; the other part is to perform edge enhancement on the composite image of the high and low-energy images to improve the image detail information. Then, based on the edge-enhanced composite image and combined with the image material information, a pre-designed color table is queried to generate the default displayed image for security inspectors to interpret. The specific process is shown in **Figure 1**.

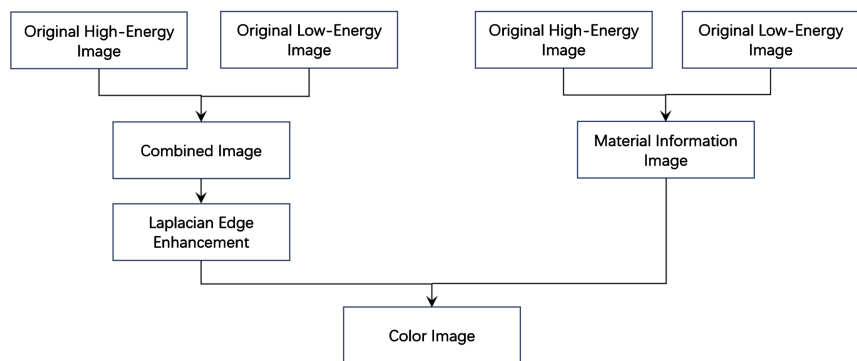


Figure 1. Data processing flowchart of default image display effect of existing equipment.

The problems faced by the above two parts of the data processing process are as follows: For the acquisition of image material information, the inevitable statistical fluctuations in the detector output signal, the inconsistent changes between high and low energies of dual-energy, and the possible large signal deviations of individual detectors will all affect the accuracy of material discrimination. In addition, the number of data bits of the existing material information is limited, and the generation method of the material table queried for obtaining material information from dual-energy images has certain limitations, which may lead to local steps in the material information. Reflected in the default displayed image of the equipment, this results in many color noise points and uneven color, which is unfavorable for security inspectors to interpret the images.

In view of this, this paper conducts research on image filtering and proposes a method to improve the default image display effect of dual-energy X-ray security inspection equipment. Firstly, an improved NL-Means method is studied. The idea of this method originates from the neighborhood weighted average filtering algorithm. The weight of this method is determined according to the similarity of

the gray distribution around the pixels. Therefore, this method largely balances the contradiction between smoothness and detail preservation, which is inevitable for any filtering method. In this paper, the improved NL-Means filter is applied to the original high and low-energy images and their corresponding material characteristic images to improve the phenomena of uneven image color and noise points. The derivation of material characteristic images from dual-energy data follows these steps: First, the original high-energy (E_{high}) and low-energy (E_{low}) X-ray images are preprocessed to correct detector response inconsistencies and eliminate dark current noise. Then, based on the physical principle that different materials have distinct attenuation coefficients for high and low-energy X-rays, the attenuation ratio $R = E_{low}/E_{high}$ (after normalization) is calculated pixel-wise. This ratio R is mapped to a predefined material attribution table, where specific R value ranges correspond to common materials in security inspection scenarios (e.g., organic, inorganic, metal). The resulting pixel-wise material classification map, after preliminary denoising to remove isolated misclassifications, is defined as the material characteristic image, which directly reflects the material composition distribution of the inspected items. However, this filtering method has a serious problem of low real-time efficiency, making it difficult to apply in engineering. This paper then studies three acceleration methods. The first one is to distinguish the high and low-frequency information of the image from the perspective of the image itself and apply the improved NL-Means filter to the high and low-frequency positions where details need to be preserved. The second acceleration method is to introduce the symmetric transformation of the neighborhood into the similarity neighborhood comparison by using the property of symmetric structure in the image from the perspective of the algorithm principle and structure, so as to reasonably reduce the number of structural operations and thus improve the timeliness of the method. The third one is to convert the floating-point exponential operation into a look-up table operation from the perspective of engineering practice, so as to reduce the computational cost of the computer. The processing flow of the default image display effect studied in this paper is shown in **Figure 2**.

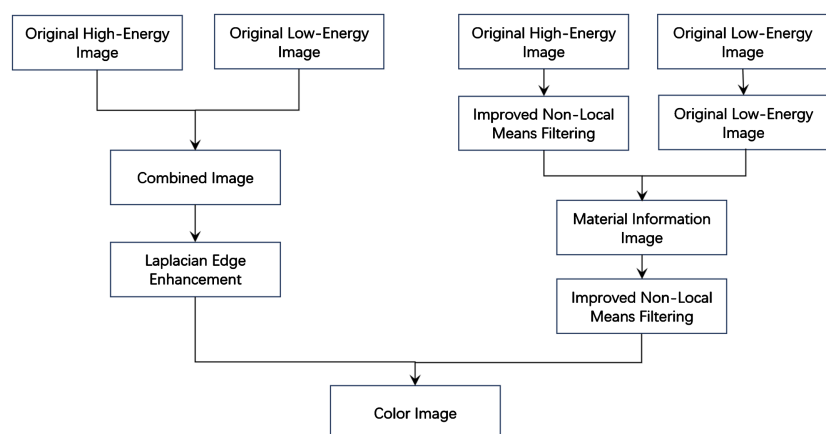


Figure 2. Processing flow of default image display effect studied in this paper.

2. Improved NL-Means Filtering Method

The purpose of image filtering is to ensure that the default displayed color image has fewer noise points and looks more uniform while maintaining good details. The overall design principle is to improve the color observation effect of the package image without affecting the performance indicators of the national standard test box A and without causing color distortion of the national standard test box B.

The idea of the NL-Means filtering algorithm originates from the neighborhood weighted average filtering algorithm and is an extension of it. The weight of this method is no longer obtained by comparing the gray value of a single pixel in the image with that of other pixels, but by comparing the gray distribution of a certain area around the pixel to be processed and its neighborhood pixels as a whole. The weight of each neighborhood pixel is determined according to the similarity of the gray distribution around the pixels. The implementation idea of the algorithm is shown in **Figure 3** [1].

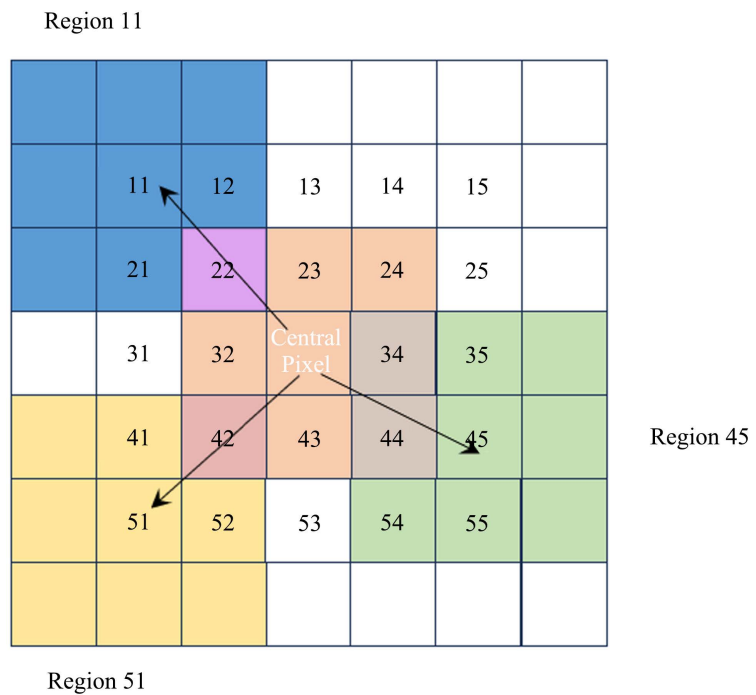


Figure 3. Schematic diagram of the implementation idea of the NL-means filtering algorithm.

When implementing the algorithm, two window sizes need to be set: one is the pixel neighborhood window size of $K \times K$, and the other is the window size of $L \times L$ for the search range of the pixel neighborhood window. That is, within the area of size $L \times L$, the NL-Means filtering algorithm is implemented with the pixel neighborhood size of $K \times K$. The $K \times K$ window slides within the area of size $L \times L$, and the contribution weight of the gray value of the central pixel of the area is determined according to the similarity of the areas.

As shown in **Figure 3**, $K=3$ and $L=5$. Pixels 11 to 55 form the 5×5 neighborhood window search range for the central pixel to be processed. Among them, the neighborhood size used to compare the similarity of gray distribution between each pixel is 3×3 . **Figure 3** shows the ranges for comparing the gray distribution similarity between area 11 (blue), area 45 (green), area 51 (yellow) and the central pixel area (red). The similarity of gray distribution can be mathematically described by the Gaussian-weighted Euclidean distance based on gray levels between the two neighborhoods (such as the central pixel area and area 11) where pixels i and j (such as the central pixel and pixel 11) are located. The specific filtering formula of the improved NL-Means filtering algorithm is shown in Formula (1) [2]:

$$NL(i, j) = \frac{\sum_L \left[e^{\frac{-W}{h^2}} \cdot f(i + L_x, j + L_y) \right] + f(i, j) \cdot W_{\max}}{W + \sum_L e^{\frac{-W}{h^2}}_{\max}} \quad (1)$$

$$W = a \times \sum_k \left\{ \left[f(i + L_x + K_x, j + L_y + K_y) - f(i + K_x, j + K_y) \right]^2 \right\} \quad (2)$$

where:

- f represents the image to be filtered.
- W_{\max} is the maximum value of W within the range L .
- a and h are empirical parameters related to the gray value of $f(i, j)$ and the signal-to-noise ratio of the overall image.

The empirical parameters a and h are determined through dataset-driven calibration: a is set to 0.001 for original high/low-energy images and 0.0008 for material characteristic images, optimized to balance noise suppression and detail preservation on a training set of 300 security inspection images (covering test boxes and real packages). h is adaptively adjusted based on the local signal-to-noise ratio (SNR) of the image: for regions with $\text{SNR} > 30$ dB, $h = 10$; for 20 dB $< \text{SNR} \leq 30$ dB, $h = 15$; for $\text{SNR} \leq 20$ dB, $h = 20$. This adaptive rule ensures the filter performs stably across different noise levels in security inspection scenarios.

It should be noted that the improvement of Formula (1) compared with the conventional method [2] is that W_{\max} is added to the denominator, and $f(i, j) \times W_{\max}$ is added to the numerator. The purpose of this is to further enhance the weight of the pixel to be processed, especially when the target pixel is located at the edge with large gradient changes, its weight is significantly enhanced compared with the conventional method.

To more intuitively illustrate the processing effect of the improved NL-Means filtering method, local images of the B6550 test box shown in **Figure 4(a)**, **Figure 5(a)**, **Figure 6(a)**, and **Figure 7(a)** are taken as examples, and the comparison results of their processing effects with those of the typical median filtering [3] and mean filtering [4] are given. The template size of the median filtering [3] and mean filtering is 5×5 .

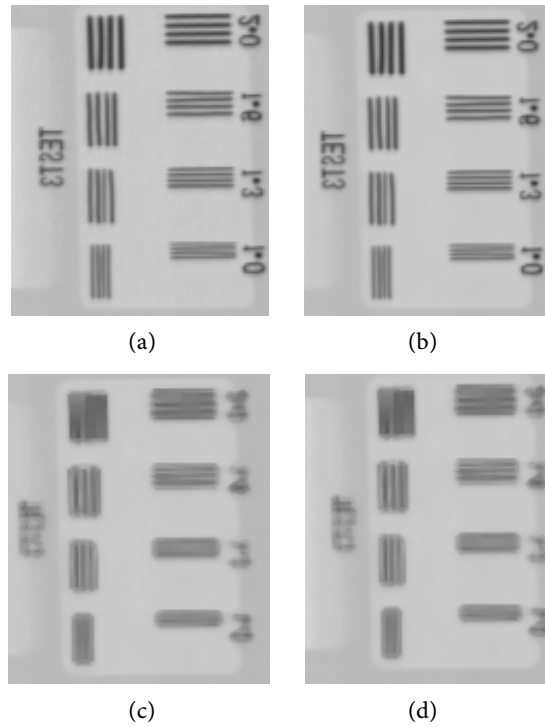


Figure 4. Local image 1 of the national standard test box A of the CMEX-B6550 equipment. (a) Original image, (b) Filtering effect of the proposed algorithm, (c) Median filtering effect, (d) Mean filtering effect.

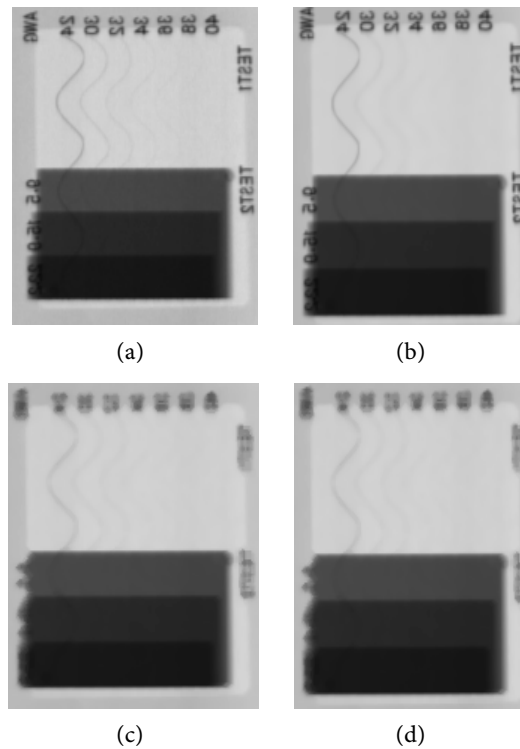


Figure 5. Local image 2 of the national standard test box A of the CMEX-B6550 equipment. (a) Original image, (b) Effect of the proposed algorithm, (c) Median filtering effect, (d) Mean filtering effect.

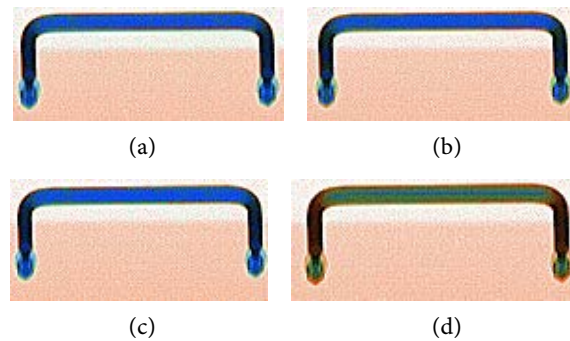


Figure 6. Local image 1 of the national standard test box B of the CMEX-B6550 equipment. (a) Original Image, (b) Filtering Effect of the Proposed Algorithm, (c) Median Filtering Effect, (d) Mean Filtering Effect.

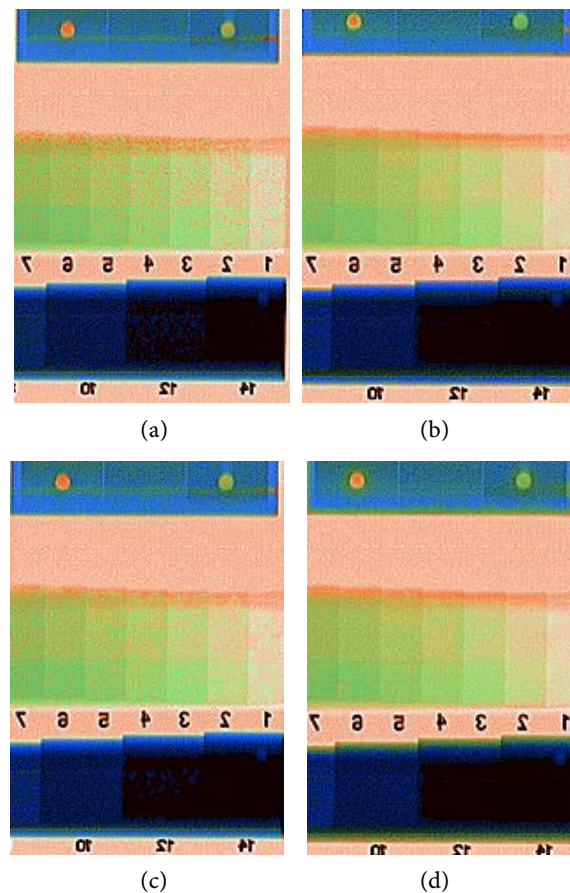


Figure 7. Local Image 2 of the national standard test box B of the CMEX-B6550 equipment. (a) Original image, (b) Effect of the proposed algorithm, (c) Median filtering effect, (d) Mean filtering effect.

Figure 4 and **Figure 5** show the original image, the processing result of the improved NL-Means filter, the processing result of the median filter, and the processing result of the mean filter from left to right. It is not difficult to see that the improved NL-Means filtering method studied in this paper can fully smooth the noise while maintaining good image details. It should be pointed out that this fil-

tering quality is very important and necessary for the spatial resolution and penetration resolution indicators. On the contrary, the traditional median filtering [3] and mean filtering do not have such quality [5].

Figure 6 and **Figure 7** show the original image, the processing result of the improved NL-Means filter, the processing result of the median filter, and the processing result of the mean filter from left to right. It is not difficult to see that the improved NL-Means filtering method studied in this paper is superior to the median and mean filtering methods in maintaining image color information while smoothing the noise well. **Figure 8** takes the image of the national standard test box B collected by the CMEX-D8380 dual-channel equipment as an example to show the actual processing effect of the above-mentioned improved NL-Means filtering method.

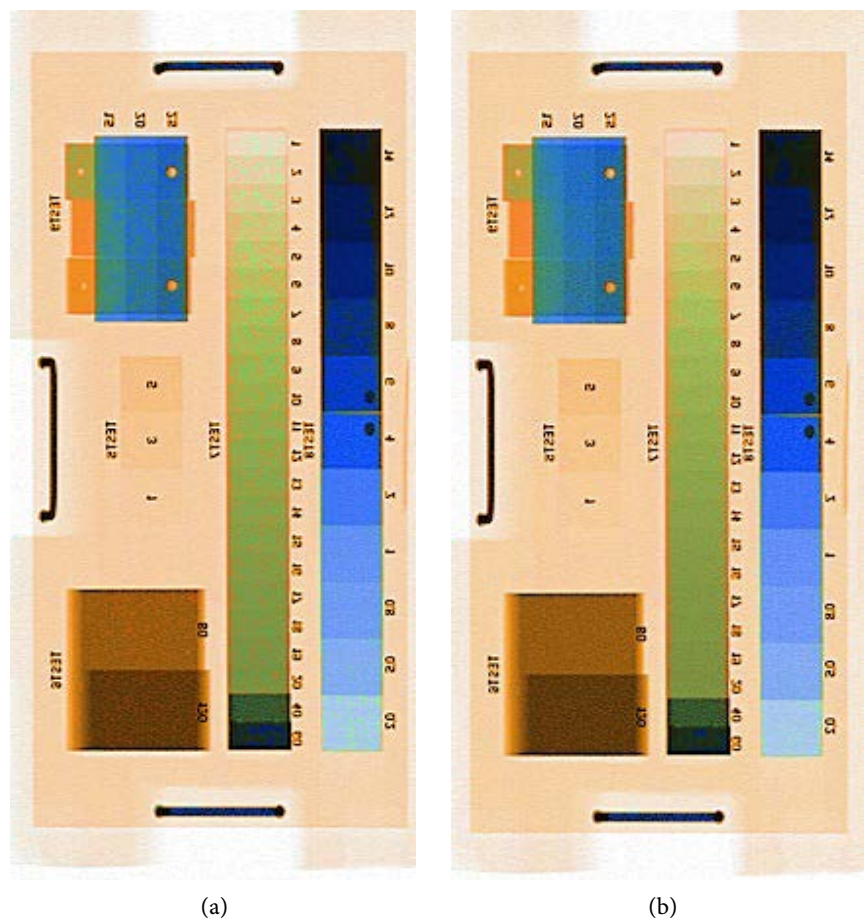


Figure 8. Image of the national standard test box B collected by the CMEX-D8380 dual-channel equipment. (a) Effect without the proposed filtering algorithm, (b) Effect with the proposed filtering algorithm.

By observing the results shown in **Figure 8**, especially the aluminum step part, the image color of the result obtained by the existing default image display process is not uniform enough, and the noise points are relatively obvious. After processing with the improved NL-Means filtering method proposed in this paper, the

image color is relatively uniform, the noise points are significantly reduced, and the color of the international test box B shown in **Figure 8** has almost no distortion.

3. Acceleration of the Improved NL-Means Filtering Algorithm

As described earlier, the improved NL-means filtering algorithm has a serious problem of low real-time efficiency. This is mainly reflected in the fact that when calculating the filtered value of each pixel, it is necessary to perform $K^*(K+1)(L-K+1)^2$ integer additions, $(K^2+1)(L-K+1)^2$ integer multiplications, and $2L$ floating-point exponential operations. If the size of a general security inspection image is 1,024,768, then the above operations are repeated 1024*768 times for the entire image. This paper studied three acceleration methods. The first one was to selectively implement the improved NL-means filter from the perspective of the image itself. The second one was to reasonably reduce the number of structural operations based on the principle and structure of the algorithm. The third one was to convert the floating-point exponential operation into a look-up table operation from the perspective of engineering practice.

3.1. Filtering Method of Distinguishing High and Low Frequencies and Treating Them Separately from the Perspective of Images

If the gray level within the search window size of $L \times L$ of the pixel neighborhood window is relatively uniform, the $K \times K$ window slides within the area of $L \times L$, and the contribution weight of the gray value of the central pixel of the area is determined according to the area similarity. According to the descriptions of Formula (1) and Formula (2) in Section 2.2, these contribution weights will be very slightly different. In fact, in this case, for the filtering of the central pixel, the filtered value is largely equivalent to the gray average value within the range of the window size of $L \times L$. In such an area, if mean filtering is used instead of the improved NL-means filtering, only L^2 additions and 1 division are required when calculating the filtered value of each pixel, which saves time. The improved NL-means filter is still used in the high-frequency area of the image. This requires performing a gradient processing on the image before filtering, using the gradient threshold to simply distinguish high and low frequencies, and selecting the filtering method with different strategies. Taking the image of the lower right view of test box B collected by the EDS-MV6040 equipment as an example, **Figure 9** shows the actual effect of the above-mentioned filtering processing with different strategies based on frequency division. **Table 1** shows the comparison between the processing time of the above-mentioned accelerated filtering and the improved NL-means filtering method described in Section 2 of this paper, taking the images of test box A, test box B, and two actual packages collected by the EDS-MV6040 equipment from the lower right view as examples. The computer platform for comparison is an i7 CPU with a main frequency of 2.93 GHz and a memory of 3 GB.

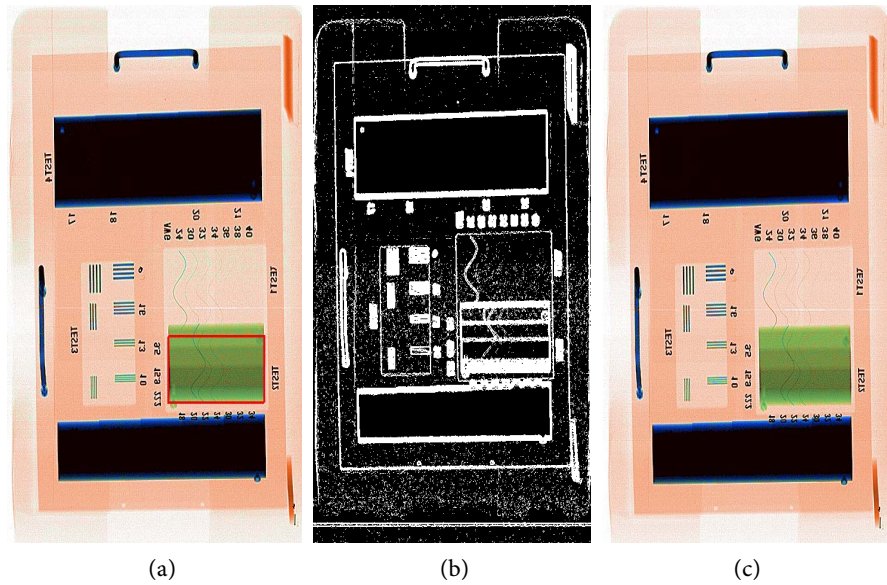


Figure 9. Lower right view image of the test box A collected by the EDS-MV6040 equipment. (a) Effect without the proposed filtering algorithm, (b) High-frequency information, (c) Effect of the filtering algorithm of treating separately.

Table 1. Time comparison before and after acceleration for images collected by the EDS-MV6040 equipment.

Image Type	Image Complexity	Image Size	Time of Improved NL-Means Filtering (ms)	Time of Filtering Method with Different Strategies Based on Frequency Division (ms)
Test Box A	Simple	460*700	700	344
Test Box B	Simple	480*700	750	369
Package 1	Moderately Complex	710*800	1109	719
Package 2	Complex	700*800	990	766

It can be seen from **Table 1** that the acceleration effect is relatively obvious when the image content is relatively simple, but the acceleration effect is not obvious when the image is complex. This is because when the image is simple, there are more low-frequency areas, the area where the mean filter is selected is large, and the area where the improved NL-Means filter is used is small, so the running time is short. On the contrary, when the image is complex, the area where the improved NL-Means filter is used is large, and the time consumption is more. Therefore, this filtering method of treating separately does not fundamentally solve the time-consuming problem of the improved NL-Means filtering.

The gradient threshold for separating high- and low-frequency regions is set to 15 (normalized to the 0 - 255 gray level range) through iterative calibration on a

dataset of 500 typical security inspection images (including test boxes, packages with various materials, and cluttered items). This threshold is determined by minimizing the classification error between manually labeled high/low-frequency regions and algorithmically segmented regions. Sensitivity analysis shows that when the threshold varies within ± 3 , the segmentation result changes by less than 5% for simple images (e.g., test boxes with clear edges) and less than 8% for complex images (e.g., cluttered packages with overlapping items), indicating good robustness to image content variations.

3.2. Reducing Structural Calculation Units by Using Symmetric Transformation from the Perspective of the Algorithm

In the NL-Means filtering algorithm, the most complex part is the calculation of the weighted Gaussian distance between two pixels. This is because for each pixel, it is necessary to calculate the distance value between it and all other pixels in the surrounding area, and calculate the weighted weight based on this distance [3].

Here, the computational complexity is reduced only from the perspective of the calculation method, which will not cause any loss in performance. Considering that the distance is symmetric, the distance between any two pixels can be calculated only once. According to this symmetry property, the weights defined in Formula (3) are also symmetric. Therefore, the total number of weight calculations can be reduced by half. Since the weight calculation takes the most time, the acceleration of the algorithm is nearly doubled.

$$d(i, j) = \|v(N_i) - v(N_j)\|^2 = \|v(N_j) - v(N_i)\|^2 = d(j, i) \quad (3)$$

Firstly, two matrices are defined: the weight normalization matrix W and the cumulative contribution matrix C , whose sizes are the same as the size of the input image. At the beginning of the algorithm, they are initialized to 0. When processing pixel i and calculating the contribution from pixel j , the obtained $w(i, j)_{y_i}$ and $w(i, j)_{y_j}$ are stored in the corresponding j and i positions in matrix C respectively. Similarly, the weight normalization matrix W is accumulated at the corresponding positions according to the weight $w(i, j)$. Therefore, when processing pixel j , it is no longer necessary to calculate the weights of the pixels where $i < j$, and only the weights of the pixels where $i > j$ need to be calculated. Finally, it is only necessary to normalize the elements of the cumulative contribution matrix C with the elements at the corresponding positions in matrix W to obtain the final restored image. The effect of this acceleration method is consistent with that of the original algorithm, as shown in **Figure 8**, and the effect diagram is not given here again. **Table 2** shows the comparison between the processing time of the above-mentioned accelerated filtering and the improved NL-means filtering method described in Section 2 of this paper, taking the images of test box A, test box B, and two actual packages collected by the EDS-MV6040 equipment from the lower right view as examples. The computer platform for comparison is an i7 CPU with a main frequency of 2.93 GHz and a memory of 3 GB.

Table 2. Time comparison before and after acceleration for images collected by the EDS-MV6040 four-view equipment.

Image Type	Image Complexity	Image Size	Time of Improved NL-Means Filtering (ms)	Time of Method with Reduced Structural Calculation Units (ms)
Test Box A	Simple	460*700	700	365
Test Box B	Simple	480*700	750	400
Package 1	Moderately Complex	710*800	1109	491
Package 2	Complex	700*800	990	500

It can be seen from **Table 2** that when the image sizes are similar, the accelerated filtering by reducing structural calculation units using symmetric transformation from the perspective of the algorithm is basically independent of the image complexity, and is nearly twice as fast as the unaccelerated one. It truly fundamentally solves the problem that the improved NL-Means filtering method is difficult to apply in engineering due to timeliness.

3.3. Converting Floating-Point Exponential Operation into Look-Up Table Operation from the Perspective of Engineering Practice

There are a large number of floating-point exponential operations in the improved NL-Means filtering algorithm, and the direct operation takes a lot of time. Within the allowable precision range, the exponential operation can be made into a look-up table form and placed in the Dll initialization stage. Querying the table to obtain the result during each calculation can save time.

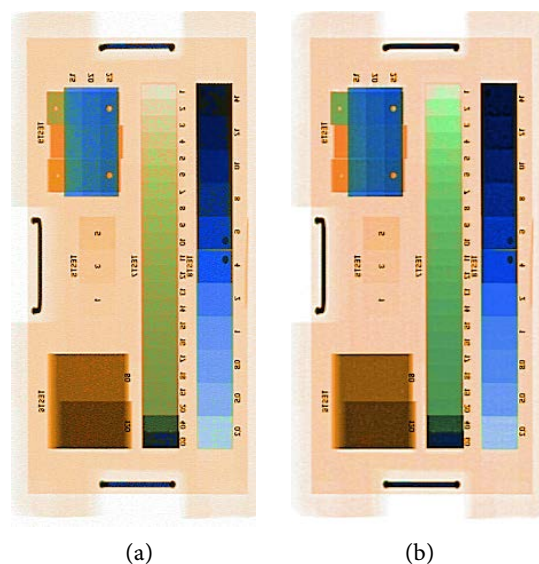
The specific method is to make the part of $e^{\frac{-W}{h^2}}$ in Formula (1) into a function. A one-dimensional global array variable Value [numLength] is defined, where numLength represents the possible range of $\frac{-W}{h^2}$. The normalized $\frac{-W}{h^2}$ is used as the element index of the array Value [numLength], and the element value is obtained and then denormalized to obtain the current value of $e^{\frac{-W}{h^2}}$. This function is placed in the Dll initialization stage. Practice has proved that this method can improve efficiency. **Table 3** takes the images of the lower right view of the test box A, test box B, and two actual packages collected by the EDS-MV6040 equipment as examples to show the comparison between the processing time of the method described in this section combined with the method described in Section 3.2 and the improved NL-Means filtering method described in Section 2 of this paper. The computer platform for comparison is an i7 CPU with a main frequency of 2.93 GHz and a memory of 3 GB.

Table 3. Time comparison before and after acceleration for images collected by the EDS-MV6040 equipment.

Image Type	Image Complexity	Image Size	Time of Improved NL-Means Filtering (ms)	Time of Floating-Point Exponential Look-Up Table Method (ms)
Test Box A	Simple	460*700	700	234
Test Box B	Simple	480*700	750	235
Package 1	Moderately Complex	710*800	1109	296
Package 2	Complex	700*800	990	313

4. Experimental Verification

Taking the image of the test box B collected by the CMEX8380 equipment, the image of an ordinary package collected by the CMEX B6550 equipment, and the image of an ordinary package collected by the EDS-MV6040 equipment as examples, the comparison results between the default displayed images obtained by the method studied in this paper (with the accelerated processing in Sections 3.2 and 3.3) and the default displayed images of the existing FISCAN equipment are given. As shown in **Figures 10-12**, it is not difficult to see that whether it is the color uniformity and noise level of the image of the test box B or the overall observation effect of the image of the ordinary package, the default image display effect improved by the method proposed in this paper is significantly better than that of the existing equipment. **Figure 10** shows the comparison result of the image of the test box B collected by the CMEX8380 equipment. **Figure 11** shows the comparison result of the image of an ordinary package collected by the CMEX B6550 equipment.

**Figure 10.** Lower right view image of the test box A collected by the CMEX8380 equipment. (a) Default display effect of existing images, (b) Improved default display effect of the proposed method.

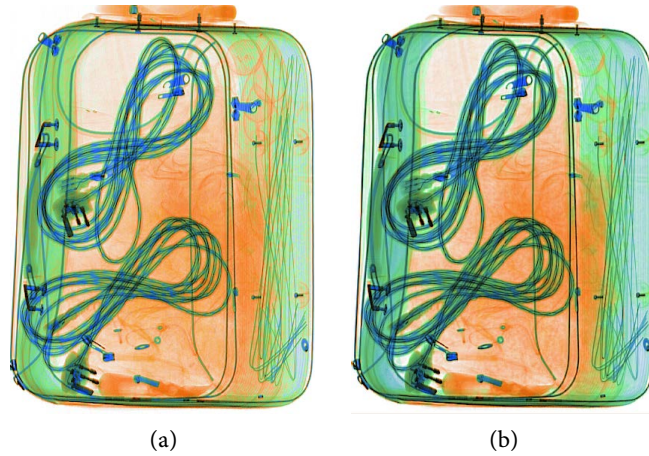


Figure 11. Comparison result of the image of an ordinary package of the CMEX B6550 equipment. (a) Default display effect of existing images, (b) Improved default display effect of the proposed method.

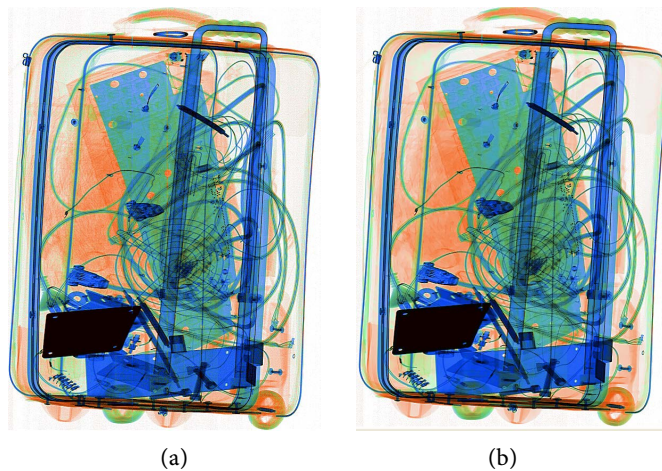


Figure 12. Comparison result of the image of an ordinary package of the EDS-MV6040 equipment. (a) Default display effect of existing images, (b) Improved default display effect of the proposed method.

Figure 12 shows the comparison result of the image of an ordinary package collected by the EDS-MV6040 equipment.

To objectively quantify the effect of the improved NL-Means filtering, **Table 4** is presented to compare the differences between original images and filtered images using PSNR, SSIM, and Color Variance—metrics that assess noise suppression, detail preservation, and color uniformity respectively.

Table 4. Objective metrics comparison between original images and improved NL-means filtered images.

Image Type	Processing Method	PSNR (dB)	SSIM	Color Variance
Test Box A	Original Image	28.36	0.721	18.65
	Improved NL-Means	35.82	0.915	6.32

Continued

Test Box B	Original Image	27.91	0.703	19.21
	Improved NL-Means	34.95	0.902	7.15
Package 1	Original Image	26.84	0.687	21.38
	Improved NL-Means	33.76	0.889	8.24
Package 2	Original Image	26.19	0.665	22.54
	Improved NL-Means	32.98	0.876	9.01

Note: PSNR (Peak Signal-to-Noise Ratio) reflects the noise suppression ability of the processing method, with higher values indicating better noise reduction; SSIM (Structural Similarity Index) evaluates the preservation of image structural information, with values closer to 1 indicating better retention of original image details; Color Variance quantifies the uniformity of image color distribution, with lower values indicating more uniform image colors.

5. Conclusions

To improve the default image display effect of the dual-energy X-ray security inspection equipment, this paper conducts research on image filtering, and the main contents include two aspects:

1) An improved NL-Means filtering method is studied. Adaptive filtering is performed on the original high and low-energy images and their corresponding material characteristic images respectively. On the premise of ensuring that the performance indicators of the national standard test box A are not reduced and the color of the national standard test box B is not distorted, the phenomenon of uneven image color is well improved, and the color noise points are significantly reduced.

2) Aiming at the problem of poor timeliness of the improved NL-Means filtering algorithm, three acceleration methods are studied. The first one is to distinguish high and low frequencies from the perspective of the image and selectively use the time-consuming improved NL-Means filter. The second one is to reduce the structural calculation units by using symmetric transformation from the perspective of the algorithm principle and structure, so as to reduce the time consumption of the filtering algorithm in principle. The third one is to convert the floating-point exponential operation into a look-up table method from the perspective of engineering practice. The comparison results show that the first acceleration method is related to the image complexity, while the second one is independent of the image complexity. It is determined to combine the second and third acceleration methods as the acceleration method of the improved NL-Means filtering algorithm.

The experimental results show that after processing with the method proposed in this paper, the default image display effect of the dual-energy X-ray security inspection equipment has greatly improved image color uniformity, significantly reduced noise, good overall image observation effect, and bright colors, which provides a good foundation for the subsequent interpretation of security inspec-

tors and image processing and analysis.

This study has certain limitations: Although the combination of symmetric transformation and look-up table acceleration reduces the runtime by 2 - 3 times, the processing time for complex images (e.g., cluttered packages with overlapping items) is still 296 - 313 ms, which may not meet the ultra-low latency requirements of high-throughput security inspection scenarios (e.g., 100+ images per second). Future work will focus on further optimizing runtime by leveraging parallel computing architectures: 1) Implementing the improved NL-Means filter on GPU (Graphics Processing Unit) using CUDA (Compute Unified Device Architecture) to parallelize pixel-wise filtering operations; 2) Exploring multi-threaded parallelism on multi-core CPUs to split image regions for concurrent processing. These extensions are expected to reduce the runtime of complex images to below 100 ms, further expanding the engineering application scope of the proposed method.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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