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RESEARCH ARTICLE

Digital three-stage recursive-separable image processing filter with variable sizes of scanning multielement aperture

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Abstract

Objectives. The main aim of digital image processing is to increase clarity while maintaining image quality and eliminate noise. However, the amount of information contained in digital image files is growing year after year. This circumstance negatively affects processing time, critical for systems with high load requirements on the computing platform. In this regard, the use of digital filters which enable a reduction to the processing time of incoming data is important. In order to resolve this issue, adaptive filters with different sizes of multielement processing aperture are being developed to improve image clarity and preserve image details. Filters with adaptive properties are able to change their parameters during data processing, and provide maximum performance as the aperture size increases. The aim of the work is to develop a type of recursively separable digital filter with variable sizes of a scanning multielement aperture which allows the number of computational operations to be reduced while maintaining the efficiency of filtering input data (images).

Methods. The work used recursive-separable methods and algorithms to construct digital filters.

Results. An algorithm for the recursive-separable implementation of a digital filter is described, and the final view of the processing aperture and its three-dimensional appearance are presented. In order to evaluate the performance of the filter, a comparison of the developed algorithm with the classical two-dimensional convolution algorithm was carried out. The experiment was performed using images of various sizes and consisted of determining the time spent on the process of processing the test image. The study established that the processing time of a test image using the developed filter is on average 5 times less than the time taken by the classical two-dimensional convolution algorithm. The optimal coefficients for magnifying the central element and raising the positive part of the aperture of a digital filter were determined, enabling the efficiency of its use to be enabled.

Conclusions. The studies show the effectiveness of using the developed recursive-separable two-dimensional filter to improve image clarity and reduce the time spent on processing.

Keywords: digital image processing, digital filters, recursion, separability, increased image clarity, speed

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НАУЧНАЯ СТАТЬЯ

Цифровой трехкаскадный рекурсивно-сепарабельный фильтр обработки изображений с изменяемыми размерами сканирующей многоэлементной апертуры

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Резюме

Цели. Основными целями цифровой обработки изображений являются повышение их четкости при сохранении качества изображения и устранение шумов. Однако объемы информации, содержащейся в файлах цифровых изображений, растут из года в год. Это обстоятельство негативно сказывается на времени их обработки, что критично для систем с высокими требованиями к нагрузке на вычислительную платформу. В связи с этим актуальным становится применение цифровых фильтров, позволяющих сократить время обработки поступающих данных. Для решения этой задачи разрабатываются адаптивные фильтры с различными размерами многоэлементной апертуры обработки, которые позволяют повысить четкость и сохранить детали изображения. Фильтры с адаптивными свойствами способны изменять свои параметры в процессе обработки данных, обеспечивая максимальное быстродействие при увеличении размеров апертуры. Целью работы является разработка рекурсивно-сепарабельного цифрового фильтра с изменяемыми размерами сканирующей многоэлементной апертуры, позволяющего сократить количество вычислительных операций при сохранении эффективности фильтрации входных данных (изображений).

Методы. В работе использовались рекурсивно-сепарабельные методы и алгоритмы построения цифровых фильтров.

Результаты. Описан алгоритм рекурсивно-сепарабельной реализации цифрового фильтра, а также представлен итоговый вид апертуры обработки и ее трехмерный вид. Для оценки быстродействия фильтра проведено сравнение разработанного алгоритма с алгоритмом классической двумерной свертки. Эксперимент проводился с использованием изображений различных размеров и заключался в определении времени, затраченного на процесс обработки тестового изображения. Установлено, что время обработки тестового изображения с применением разработанного фильтра в среднем в 5 раз меньше, чем время, затрачиваемое алгоритмом классической двумерной свертки. Определены оптимальные коэффициенты увеличения центрального элемента и поднятия положительной части апертуры цифрового фильтра, позволяющие повысить эффективность его применения.

Выводы. Проведенные исследования показывают эффективность использования разработанного рекурсивно-сепарабельного двумерного фильтра для повышения четкости изображений и уменьшения затрачиваемого на обработку времени.

Ключевые слова: цифровая обработка изображений, цифровые фильтры, рекурсия, сепарабельность, повышение четкости изображений, быстродействие

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INTRODUCTION

The first preliminary step in image analysis is, as a rule, digital image processing. The quality of this stage can dramatically affect the results of subsequent analyses. Digital processing, including digital filtering, is used to resolve such problems as resolution enhancement, restoration of 'spoiled' objects in the image, clarity enhancement, and colourisation [1].

The main purpose of image filtering is to improve the clarity and quality of images and to remove noise. However, the amount of information contained in digital image files is growing from year to year [2]. This adversely affects the ability of digital filters to perform fast and high-quality processing of incoming data. One of the ways to resolve this problem is to increase the speed of digital filters by reducing the number of computational operations required for processing. It is also important to ensure the variability of their use and the possibility of parameter correction during operation. An effective solution is to develop adaptive filters which can change their parameters during image processing, in order to maintain performance while increasing the aperture size. In adaptive filters, the processing speed always remains constant for specific image sizes, regardless of the processing aperture size.

FILTERS WITH ADAPTIVE PROPERTIES

Adaptive filters are a class of filters in which the parameters are adjusted during operation according to the characteristics of the input data [3]. For each fixed set of parameters, an adaptive filter is a linear device, since there is a linear dependence between its input and output signals [4, 5].

Adaptive filters are of two types [6, 7]:

- transversal, i.e., filter with finite impulse response;
- recursive, i.e., filter with infinite impulse response.

Adaptive filters are widely used in various fields such as signal processing, computer vision, image processing, among others. In the latter two cases, their main purpose is to clean photo and video information from noise overlapping in spectrum with the useful signal, or when the noise bandwidth is undefined and cannot be specified initially [8]. The use of adaptive filters can significantly improve the efficiency and quality of data processing in various applications where automatic adjustment to changing conditions or requirements is necessary [4, 9].

CONSTITUENT ELEMENTS

Constituent recursive cells (recirculators) are used in the design of recursive filters. Recirculators are recursive cells which perform row-by-row (line recirculator, LR) and frame-by-frame (frame recirculator, FR) processing of the input image matrix [10]. Their functionality is to perform a two-dimensional discrete convolution procedure in which the input data is processed according to a given impulse response of the recirculator. The impulse response can be represented as a unit matrix (row or column of size $N \times 1$ elements). Figure 1 shows the forming recursive cells by n_1-row (LR) (a) and by n_2-frame (FR) (b), implementing the corresponding

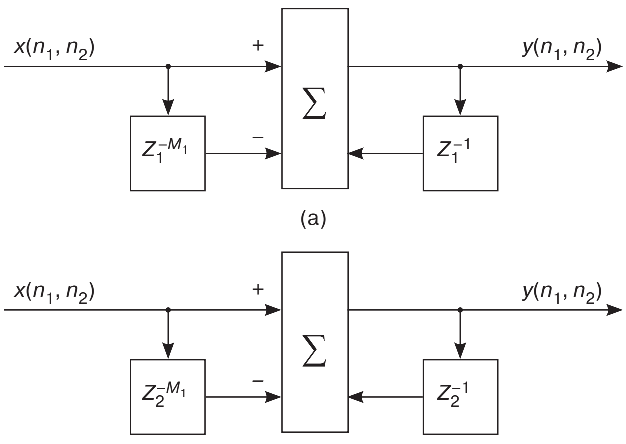


Fig. 1. Recirculator diagrams:
(a) by n_1-row, (b) by n_2-frame

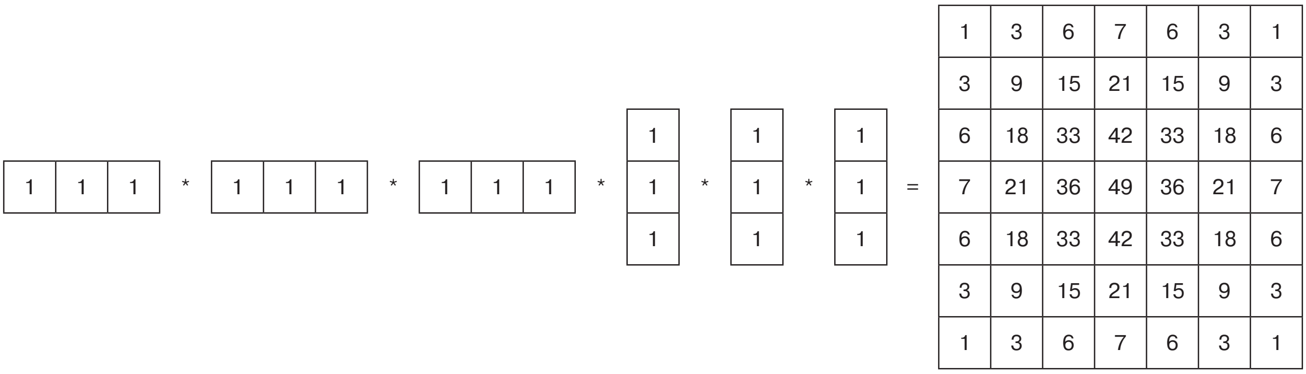


Fig. 2. Recursive-separable filter implementation algorithm

orthogonal directions of moving average processing. LR recirculator performs processing by the row of the input data matrix, and FR—by the column of this matrix; $x(n_1, n_2)$ is input data; $y(n_1, n_2)$ is output data; Z are delay elements; M_1 is the coefficient determining the delay value on the row (integer); M_2 is the coefficient determining the delay value on the column (integer) [11, 12].

INITIAL FILTER

Development of a two-dimensional filter is based on a sequence of certain processes. As an example, let us consider the process of forming a processing aperture of 7 × 7 elements of a two-dimensional three-cascade recursive-separable filter (TRSF).

The information sequence in the form of a unit matrix of 1 × 1 element is fed to the filter input. This action allows the TRSF mask to be formed which will further enable a correct comparison of the developed algorithm with the classical two-dimensional convolution (CTDC) algorithm. In order to form the main size of the processing aperture, the specified sequence passes through three row (a row of units of size 3 × 1 elements) and three frame (a column of units of size 1 × 3 elements) recirculators. This results in a matrix of 7 × 7 elements which is the basis for forming the final mask and undergoes further modifications. Figure 2 shows the algorithm of the recursive-separable filter implementation.

As a result of the operations taking place in the filter after the input of the test information sequence in the form of a unit matrix, a TRSF mask is formed. This is presented in Fig. 3 and a three-dimensional view is shown in Fig. 4 [13].

Figure 3 shows that the TRSF mask has a positive area in the center with the size of 3 × 3 elements. Its proportional increase resulting in the change of the initial sum of coefficients of the final mask will increase the efficiency of digital image processing. The same principle is used for processing by changing the center element of the matrix (for a mask of 7 × 7 elements it is the 4th element in the 4th row).

–1	–3	–6	–7	–6	–3	–1
–3	–9	–18	–21	–18	–9	–3
–6	–18	14	58	14	–18	–6
–7	–21	58	80	58	–21	–7
–6	–18	14	58	14	–18	–6
–3	–9	–18	–21	–18	–9	–3
–1	–3	–6	–7	–6	–3	–1

Fig. 3. TRSF 7 × 7 elements mask view

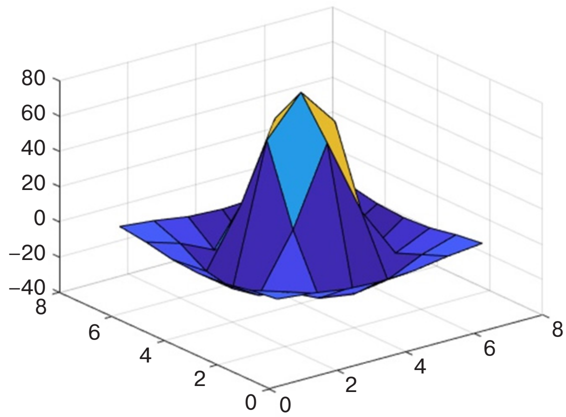


Fig. 4. Three-dimensional view of TRSF mask

The structural diagram of the TRSF with dimensionality of 7 × 7 elements is shown in Fig. 5. Here A_1 is the coefficient of increase in the values of the positive part of the mask, and A_2 is the coefficient of increase in the value of the center element of the mask. In the first branch of the TRSF, the formation of a mask of dimension 3 × 3 elements takes place. This is necessary, in order to compensate the negative part and form the positive center of the final mask due to the delay elements Z. The second branch of the filter forms the basic matrix of 7 × 7 elements. The third branch of the TRSF is necessary, in order to compensate the negative part of the mask by adding the residual to the center element of the main matrix, and to enable its

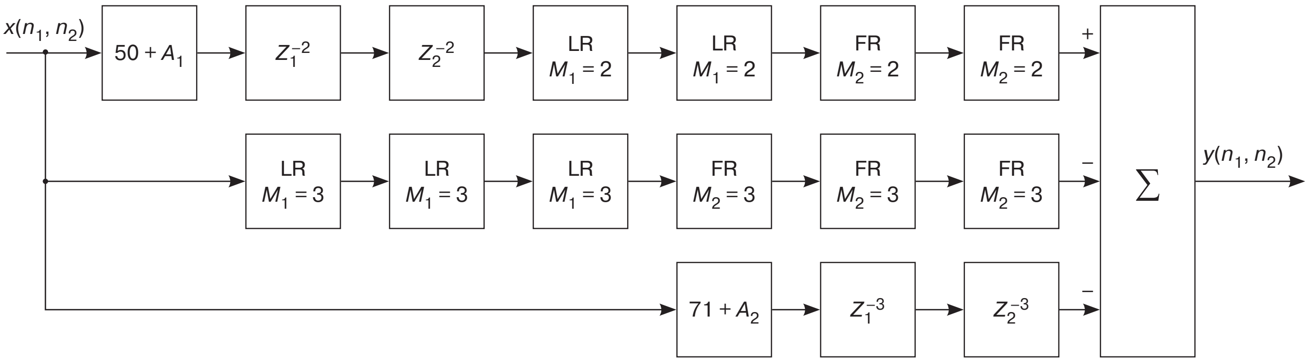


Fig. 5. Structural diagram of TRSF

adjustment by the user. The output data of the branches are aggregated, in order to form the filter output. For the second and third branches the aggregation is performed with sign inversion.

DESCRIPTION OF THE TRSF FILTER MODIFICATION PRINCIPLES

For the proper functioning of the adaptive TRSF, it is necessary to ensure its correct response to the user-defined value of the processing aperture dimensions. In this case, the operation takes place exclusively with odd values of dimensions (9 × 9, 11 × 11, 13 × 13, etc.). It is important to take into account the change of the coefficients of the center mask recirculators to the changes of the main filter mask recirculators in the ratio 1 : 2. Thus when the final size of the filter's main aperture changes, the size of its center mask also changes, albeit only every second increase in the size of the main mask. One recirculator always remains unchanged because the filter uses an odd number of recirculators. The size of the impulse response value matrix should be 3 × 1 or 1 × 3 elements. In this case, for a given dimensionality of 9 × 9, the coefficients of the line and frame recirculators will be equal to 4 (unit matrix of 4 × 1 elements) and 4 (unit matrix of 1 × 4 elements), respectively. For a dimensionality of 11 × 11, they will be equal to 5 (unit matrix of 5 × 1 elements) and 5 (unit matrix of 1 × 5 elements).

It is important to note that in the center part of the filter a smaller mask is generated when compared to the main one. This central part is necessary, in order to balance the sum of the outer and central parts of the final mask, to bring its sum to zero and to preserve normal brightness of the processed image. A similar balance of the outer and central parts of the final mask can be observed in the Laplacian filter for 'eight neighbors', where the sum of all coefficients is equal to zero [14]. When increasing the size of the mask, the normal ratio between the sizes of the outer and central regions must be maintained, in order to change its three-dimensional appearance proportionally. This is done by varying the size of the center mask in steps of 2. For example, a 3 × 3 center mask will be used for the 7 × 7 and 9 × 9 element matrices, followed by an increase of 2 elements to a 5 × 5 element matrix, which will be used for the final 11 × 11 and 13 × 13 element matrices. This is accomplished by automated calculation of the recirculator coefficients at the bottom of the filter by entering the size of the desired filter aperture. Thus, every other possible value of the mask size, starting at 3 × 3, will affect the change in the size of the inner mask. For example, at dimension 7 × 7, the upper left corner of the mask is at position $x(n_1 - 1, n_2 - 2)$. Then, at the next possible value of the mask dimension (starting at 5 × 5), the shift factor of the inner mask will change to 1. Thus, at 5 × 5, the shift will be 2 (instead of 1). This is because the size of the inner mask will also decrease by 1 cell and become 1 × 1. This process will continue, and when the dimension of the main mask is 9 × 9 and the inner mask is 3 × 3, the shift will be 3.

The dependence thus described can be programmatically expressed as a function using the parameters of matrix aperture sizes. The shift coefficient of the inner mask will be equal to the difference between the size of the main mask and the size of the center mask divided by two. For example, for a size of 17 × 17, we get: (17 − 7)/2 = 5. Consequently, the matrix is shifted by 5 elements.

This process works correctly for masks of any size. First, the total number of cells in the mask is calculated. For example, in the case of a 9 × 9 mask it is 81, and for a 7 × 7 mask it is 49. Then all elements of the mask are aggregated up, and this sum is divided by the previously calculated sum of elements of the positive center of the final mask. The result is used to create a new mask in the upper part of the filter. The initial mask is subtracted from it, and as a result, the final values are formed in the cells. Aggregating them makes the whole mask (its values) equal to 0.

Modified filter should be configurable using two input coefficients. One of these coefficients will be

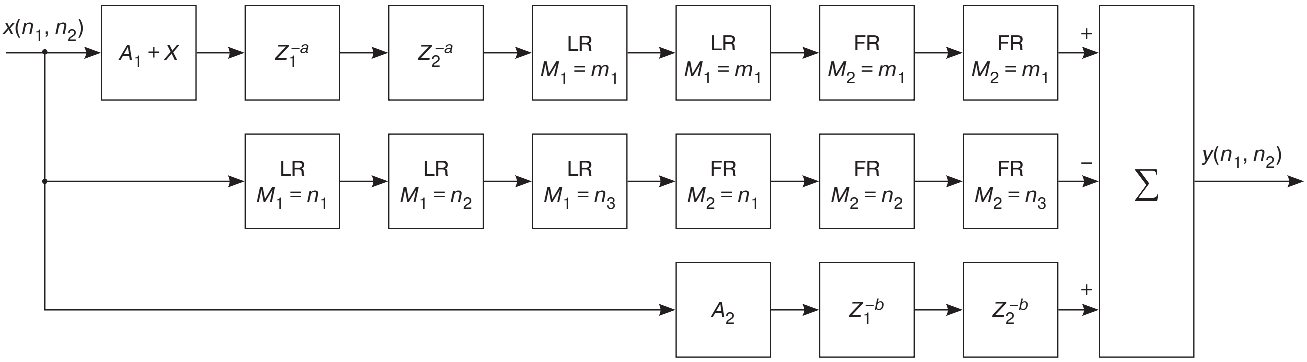


Fig. 6. Structural diagram of TRSF

Table 1. Dependence of filter parameters on the change of mask size

Set size	LR and FR coefficient	Inner mask size	LR and FR for the inner mask	Shift coefficient of the inner mask
5 × 5	2 and 2	1 × 1	1 and 1	3
7 × 7	3 and 3	3 × 3	3 and 3	3
9 × 9	4 and 4	3 × 3	3 and 3	4
11 × 11	5 and 5	5 × 5	5 and 5	4
13 × 13	6 and 6	5 × 5	5 and 5	5
15 × 15	7 and 7	7 × 7	7 and 7	5
17 × 17	8 and 8	7 × 7	7 and 7	6

used to increase the values of the center part of the mask by a specified amount. The second coefficient will be used to increase the value of the center element of the mask.

The patterns used to create the filter are illustrated in Table 1 which shows: the values of the recirculator coefficients; the size of the center mask; the number of recirculators for convolution; and the shift values of the center mask for different mask sizes from 5 × 5 to 17 × 17.

On the basis of the modification principles described above, a structural scheme of the filter, presented in Fig. 6, can be built: X is the coefficient of equalization of the sums of the central and external masks; A_1 is the coefficient of increase of the values of the positive part of the mask; A_2 is the coefficient of increase of the value of the central element of the mask; Z_1 and Z_2 are the mask shift coefficients (dependent on the variables $-a$ and $-b$, calculated automatically in the filter code); m are the row and frame recirculators coefficients for the positive branch; n are the row and frame recirculators coefficients for the negative branch.

STUDY OF THE DEVELOPED FILTER PERFORMANCE SPEED WHEN INCREASING THE SIZE OF THE PROCESSING APERTURE

Three images of different dimensionality were used for experimental studies: 640 × 480 elements of *tiff* format; 1280 × 720 elements of *bmp* format; and 3000 × 2000 elements of *jpeg* format. In the study, 7 × 7, 9 × 9 and 11 × 11 masks were used for each filter. Image processing was performed on a personal computer with the following characteristics: operating system—Windows 10; processor—12th Gen Intel(R) Core(TM) i5-12400F 2.50 GHz; RAM—32 GB. The measurement of the filter runtime was performed 10 times in each experiment and the average value was calculated.

The results of the experimental study determined the dependencies of processing speed on aperture size for each of the three images. The average values of processing time for CTDC and TRSF and their compiled MEX-functions[1] were estimated using the time

[1] Minimum EXcluded, algorithm for finding the minimum missing number.

Table 2. Average values of image processing time

Image 640 × 480, *tiff* format				
Filter mask size	Processing time, s			
	MATLAB		MEX	
	CTDC	TRSF	CTDC	TRSF
7 × 7	0.6318	0.0995	0.1187	0.0891
9 × 9	4.2060	0.0969	3.1092	0.0951
11 × 11	5.2562	0.0979	4.1090	0.0884
Image 1280 × 720, *bmp* format				
Filter mask size	Processing time, s			
	MATLAB		MEX	
	CTDC	TRSF	CTDC	TRSF
7 × 7	1.8361	0.3211	0.3622	0.2915
9 × 9	16.4342	0.3256	15.0594	0.2572
11 × 11	24.5264	0.3413	17.3964	0.2912
Image 3000 × 2000, *jpeg* format				
Filter mask size	Processing time, s			
	MATLAB		MEX	
	CTDC	TRSF	CTDC	TRSF
7 × 7	12.3788	2.4025	2.4289	2.1971
9 × 9	30.3757	2.3876	12.3612	2.1965
11 × 11	45.5701	2.2715	19.3326	2.1916

measurement procedure from *MATLAB*[2] software. The results of measuring the processing speed for the three images are presented in Table 2.

Figure 7 shows the graphs of processing time dependence on the filter aperture size for an image of 640 × 480 elements.

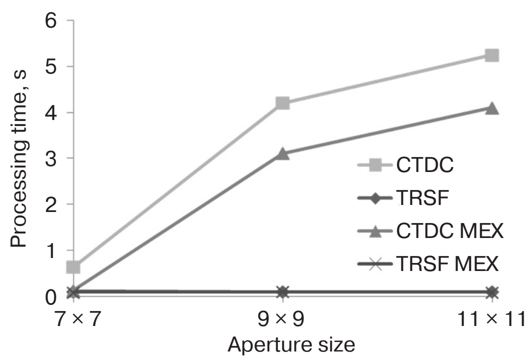


Fig. 7. Graph of performance dependence on the aperture size for 640 × 480 image (*tiff*)

Figure 8 shows the graphs of processing time dependence on the filter aperture size for a 1280 × 720 element image.

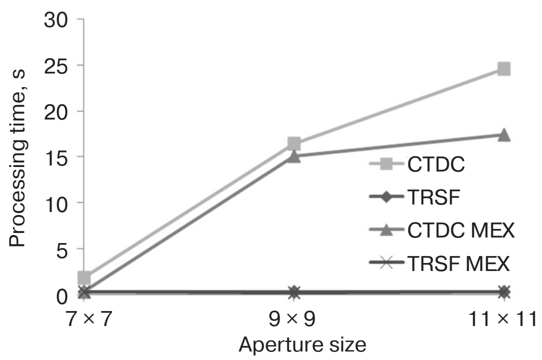


Fig. 8. Graph of performance speed dependence on the aperture size for 1280 × 720 image (*bmp*)

Figure 9 shows the graphs of processing time dependence on the filter aperture size for a 3000 × 2000 element image.

[2] https://www.mathworks.com/products/matlab.html. Accessed September 20, 2023.

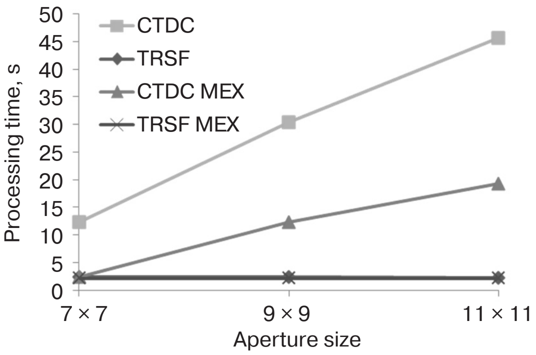


Fig. 9. Graph of performance speed dependence on the aperture size for 3000 × 2000 image (*jpeg*)

From the graphs presented above we can see the gain in performance of the developed filter when the processing aperture grows in comparison with the CTDC algorithm.

The next step is to evaluate the effect of TRSF aperture growth on its operating time. Values of aperture mask size from 7 to 25 in steps of 2, as well as 49, 75, and 99 were used. The values of coefficients in all calculations were the same and equal to: $A_1 = 10$, $A_2 = 0$. The results of measurements are summarized in Table 3.

Table 3. Time consumption for image filtering

Mask size	Processing time, s
7	2.46
9	2.39
11	2.24
13	2.27
15	2.33
17	2.29
19	2.31
21	2.32
23	2.31
25	2.33
49	2.56
75	2.62
99	2.49

It can be concluded that changing the filter aperture leads to insignificant changes in the speed of the TRSF algorithm in the range of 2.24 to 2.62 s.

ESTIMATION OF CHANGES IN THE NUMBER OF TV LINES IN THE PROCESSED IMAGES

When developing new algorithms for digital image processing, it is important not only to improve their performance, but also not to lose useful information stored in the images themselves, as well as to improve their quality (increase clarity, remove noise, etc.) to an ideal level.

The study was conducted by measuring the number of television lines (TVL) in the processed images while varying the coefficients A_1 and A_2. This is necessary, in order to test the filter's ability to keep fine details of images clear [15]. Formula [12] was used to convert the number of 'cycles per pixel' (modulation transfer function, MTF50) obtained when measuring resolution in *Imatest*[3] software into TVL:

$$\mathrm{TVL} = \left(\frac{\mathrm{CPP}}{0.5}\right) \times \text{limit resolution},$$

where CPP is the number of 'cycles per pixel', limit resolution (in TVL) is the value of the number of pixels in the width of the image.

The frame obtained by the active-pulse television measuring system[4] (Fig. 10) was taken as a test image [16, 17].

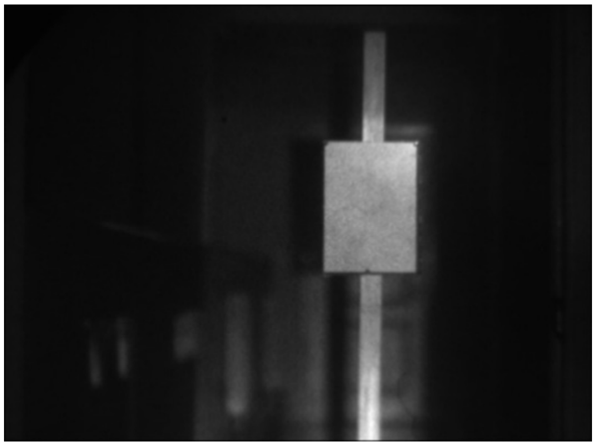


Fig. 10. Test image

This measurement was performed in order to determine the optimal values of the A_1 and A_2 coefficients, and to determine the fact of the best processing when changing either A_1, or A_2, since changing them independently of each other led to different results. Firstly, the A_1 coefficient was varied from 1 to 50, then

[3] https://www.imatest.com/. Accessed September 20, 2023.

[4] Kapustin V.V. *Active-impulse television measurement systems with increased immunity to optical interference*: Cand. Sci. (Eng.). Tomsk: 2017. 118 p. (in Russ.).

the A_2 coefficient was varied in the same range. The TVL value for the original image is 158. Figure 11 shows the dependence of TVL values on the A_1 coefficient.

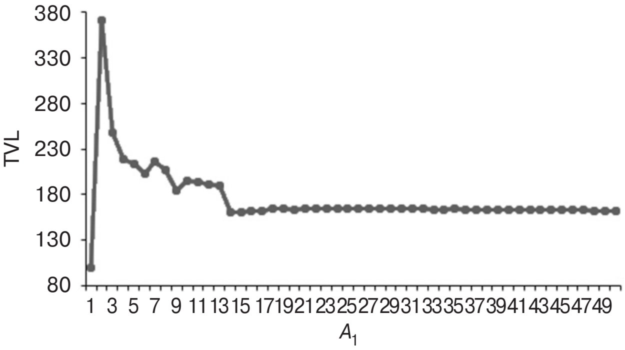
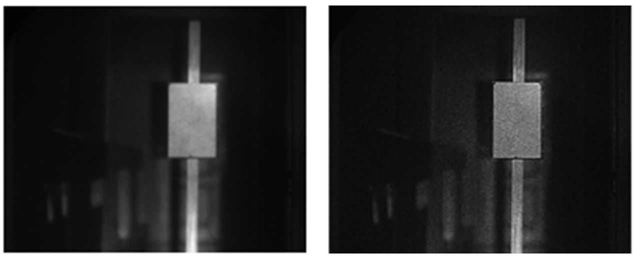


Fig. 11. Dependence of TVL values on the magnification factor of the positive part of the mask A_1

As can be seen from the results obtained, increasing the A_1 coefficient from 15 and more does not affect the final number of TVL. Image resolution before and after processing is practically unchanged, i.e., filtering loses its efficiency.

Figure 12 shows an example of processing the original image by a filter with the optimal value of the coefficient $A_1 = 1$.



(a) (b)

Fig. 12. Images before (a) and after (b) processing with the filter with optimal coefficient A_1

Results of measurements of TVL quantity at change of A_2 coefficient are shown in Fig. 13.

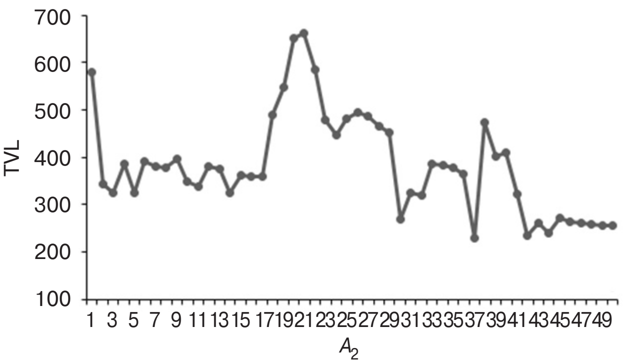
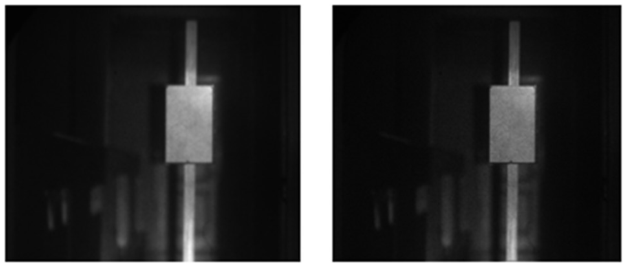


Fig. 13. Dependence of TVL values on the change of the magnification factor of the central element of the mask A_2

Figure 14 shows an example of processing the original image by a filter with the optimal value of the coefficient $A_2 = 21$.



(a) (b)

Fig. 14. Images before (a) and after (b) processing with the filter with optimal A_2 coefficient

Based on the above graphs and images, it can be concluded that changing the A_2 coefficient gives good results over the whole range of values.

CONCLUSIONS

The paper presents a modified TRSF for image clarity enhancement. The principles of its modification are described and the structural scheme is given. A study of the speed and efficiency of image processing provided by the proposed modification of the filter is performed. The time spent on image processing is 5.3 times less on average than the time spent on processing for the CTDC.

The results of evaluating the influence of the coefficient of increasing the value of the positive central aperture and increasing the value of the central element of the filter mask on the characteristics of processed images are presented herein. This study established that the value of the central element of the mask has a stronger influence on the parameters of the processed image. Its change allows the image quality to be enhanced more significantly than when increasing the positive central aperture of the filter. The study also established the optimal values of filtering coefficients A_1 and A_2.

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Authors' contributions

A.V. Kamenskiy—setting the aim and objectives of the research, processing methods, scientific editing of the article.

T.M. Akaeva—planning the research, writing the text of the article, interpreting and summarizing the results.

D.A. Grebenshchikova—conducting research, writing the text of the article.

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