High-speed recursive-separable image processing filters with variable scanning aperture sizes

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Abstract

In the process of development of computer technologies, the number of areas of their application naturally grows and, along with it, the complexity of the tasks to be solved, which entails the need for new research. Similar tasks include digital filtering of images in the field of medical technologies and active-pulse television measuring systems. There are many methods and algorithms of digital filtering designed to solve the problem of improving the quality; algorithms that can improve the quality of images while reducing computational costs are widely used. High demands, which are made due to the constant growth in the size of the generated images, as well as the requirement for modern television systems, is real-time operation. When solving practical problems, it is required to use different filter aperture sizes, which provide an increase in quality and preservation of image details. The solution of these problems was the reason for the emergence of adaptive filters that are able to change the parameters in the process of processing the received data, while not spending additional time on processing with an increase in the size of the aperture. The paper presents the principles of constructing adaptive image processing filters, which, by obtaining an input parameter indicating the required dimension of a multi-element aperture, are able to implement the construction of the required aperture. The Laplacian "Truncated Pyramid" filter and the "double pyramid" Laplacian were modified. A feature of these filters is the oddness of the multi-element aperture, so the coefficient used to build the mask is always set to odd. When using these filters, it is possible to use two coefficients that are responsible for increasing the filtration efficiency, since, in their original form, the Laplacian filters have a sum of coefficients equal to zero. The experiment shows a comparison with high-dimensional filters that work when using classical two-dimensional convolution. The next stage of the presented research will be the application of parallel computing techniques, which will increase the speed of the developed filters.

Keywords: image processing, recursively separable filters, multi-element apertures, reduction of computational costs, machine vision, medical optics and biotechnology, vision systems in difficult weather conditions.

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Introduction

An integral part of the modern world has become images obtained, for example, in systems that solve problems in the formation of biomedical images (X-ray, computed tomography, etc. [1]) or in vision systems in difficult weather conditions [2]. The priority is to reduce the acquisition of the output image in order to bring operations closer to real-time. Speed and efficiency are important factors when using digital imaging. As a result, the question arises of reducing the number of computational operations spent on the image processing process while maintaining its efficiency.

Digital image filtering realizes the goal of eliminating noise while preserving various image details [3 – 5]. Many methods and algorithms of digital filtering are designed to solve this problem, however, the increase in the dimension of images to be digitally processed requires large expenditures for performing computational operations. When solving practical problems, it is required to use different filter aperture sizes, which provide an increase in quality and preservation of image details. However, when processing too large images, increasing the filter aperture will require a lot of time for computational operations. The solution of these problems was the reason for the emergence of adaptive filters that are able to change the parameters in the process of processing the received data, while additional processing time with an increase in the size of the aperture.

Speed is the ability of devices, devices, mechanisms to perform the work for which they are intended with the required speed [6]. This property of algorithms can be formulated differently as the possibility of implementing classical linear filtering algorithms through the use of recursive transformations, which leads to a reduction in the number of computational operations, simplification of the algorithm and gain in time costs, which is in demand in various areas of human life, where it is necessary to reduce computational costs.

In adaptive filters, the performance is always static for certain image sizes at any aperture size [7, 8]. There are some properties of systems and algorithms that provide the possibility of representing classical algorithms in a different form through some transformations. These changes affect the increase in performance by reducing the number of calculations, simplifying the algorithm, which directly affects the time spent on processing.

There are various methods for reducing computational operations. For example, they are used in digital filtering based on mathematical two-dimensional convolution [9, 10]. Since two-dimensional convolution has a number of characteristics, including the possibility of pre-selection of coefficients, as well as the presence of a noticeable difference between the number of filter coefficients and input calculations [11]. Some studies have found that it is advisable to use fast two-dimensional convolutions with an aperture size of more than 4×4 (that is, 5×5, since odd values are used in practice) [12]. When convolving with smaller apertures, there is a decrease in performance due to the complexity of decomposition into smaller sizes.

It should be concluded that in the process of solving two-dimensional problems, large amounts of data are used, which cannot be said about one-dimensional problems. That is, for example, when processing two-dimensional images, an increased degree of real-time performance is required. In the same field of image processing, this is very noticeable: a black and white image contains a large number of elements, and if we use one byte to transmit each of them, we get a high value for the amount of information that needs to be processed almost instantly. This explains the high need for speed.

1. Source filters Laplacian "Truncated Pyramid" (LTP) and Laplacian "Double Pyramid" (LDP)

The LTP and LDP filters are implemented using a recursively-separable operation algorithm, which means that the processing of the rows and columns of the matrix of image values is carried out separately. Due to the truncated shape of the processing mask, the LTP filter smoothes the image while increasing its quality.

Two-dimensional digital filter LTP in the implementation of the aperture size 7×7 is a filter, in the center of which there is a 3×3 aperture of a uniform type, which is the truncation region. At the output of this filter, a mask is obtained, which is shown in Fig. 1.

The 2D digital LDP filter in the implementation of the 7×7 aperture size is a filter with a 3×3 pyramidal aperture in the center. At the output of this filter, a mask is obtained, which is shown in Fig. 2 [13].

More details on the principles of operation of these filters can be found in [14, 15].

2. Modification of the LTP filter construction algorithm

In its basic representation, the filter generates a 7×7 mask due to the coefficients of the line and frame recirculators (LR and FR), respectively. The values specified in them serve to form the size of the mask. Accordingly, for the size 7×7, two line recirculators with coefficients of 5 and 3 and two frame recirculators with coefficients of 5 and 3 are used.

-1	-2	-3	-3	-3	-2	-1
-2	-4	-6	-6	-6	-4	-2
-3	-6	16	16	16	-6	-3
-3	-6	16	16	16	-6	-3
-3	-6	16	16	16	-6	-3
-2	-4	-6	-6	-6	-4	-2
-1	-2	-3	-3	-3	-2	-1

Fig. 1. LTP filter mask

-1	-2	-3	-3	-3	-2	-1
-2	-4	-6	-6	-6	-4	-2
-3	-6	5	19	5	-6	-3
-3	-6	19	48	19	-6	-3
-3	-6	5	19	5	-6	-3
-2	-4	-6	-6	-6	-4	-2
-1	-2	-3	-3	-3	-2	-1

Fig. 2. LDP filter mask

To create the adaptability of this filter, it is necessary to modify the filter response to a given dimension value. In this case, the work proceeds exclusively with odd aperture sizes (9×9, 11×11, 13×13, etc.). For this purpose, the sensitivity of the coefficients of the recirculators to the given values is implemented in the dependence of 1 to 2. This means that when the value of the filter size changes (always by 2 to preserve oddness), one is added to each coefficient of the recirculators. In this case, with a given dimension of 9×9, the coefficients LR and FR will be equal to 6 and 4, and for a dimension of 11×11 – 7 and 5.

However, in the other branch of the filter, a mask smaller than 7×7 is generated. This is the central mask, which will later serve to create positive elements in a certain area inside the main mask if it is bordered in the form of negative ones. This is necessary to normalize the brightness. From this we can conclude that with an increase in the size of the mask, it is advisable to provide a reaction and the size of its center. Taking into account the relation of the central mask to the outer "rings", the most appropriate option for preserving it would be to start the process of increasing the mask every other time, that is, every time the mask is doubled. In this case, the central 3×3 mask will remain at the given size of 7×7 and 9×9, but expand by one cell to 5×5 at the dimensions of 11×11 and 13×13. To do this, the sensitivity of the coefficients of the recirculators of the upper branch of the filter to the specified values is realized. That is, every second possible value of the mask size, starting from 3×3, will change the size of the inner mask.

Changing the filter dimension also affects the position of the mask generated in the upper branch. It should always be in the center of the main mask, therefore, it is necessary to provide a filter response in circuit elements z_1 and z_2. With a dimension of 7×7, the upper left corner of the mask is located on the cell $x(n_1–1, n_2–2)$. Then every other possible mask size value, starting from 5×5, will change the shift factor of the inner mask by 1. For example, at 5×5, the shift will have a value of 2 (not 1, since the inner mask size will also narrow by 1 cell and will take the size of 1×1). When with the size of the main mask 9×9 and the inner 3×3, the shift will increase to 3.

The inner mask shift factor will be equal to the value obtained by subtracting the inner mask size from the given overall mask size and dividing by two. So, with a given size of 11×11, it will turn out: $(11-5)/2=3$. Therefore, the matrix is shifted by -3.

Coefficient 25 serves to increase the positive branch of the filter and ensures the correct ratio of the sums of the inner and outer parts of the final matrix, that is, it allows you to get the sum equal to zero. So, with a mask size value of 7×7, the inner part of the mask is 3×3 cells filled with numbers 9. Their sum was – 81, when the sum of the two outer “rings” of the mask is –144. The sum of all matrix elements is – 225. Accordingly, it is necessary to add a total of 225 to the inner mask to get 144. Since the inner mask is homogeneous, it is enough to determine one number, which, when the inner mask is completely filled uniformly, gives a sum equal to the sum of the outer mask. To do this, you need to determine the number of elements in the inner mask, in this case it is 25 (because $5\times5=25$). And then divide the missing number, 225, by the number of elements of the inner mask. For a 7×7 mask, the coefficient will be 25 (because $225/25=25$).

The same should happen with inner masks of other sizes. First, the number of cells in the mask is calculated, so for a 5×5 mask it will be 25, and for a 7×7 mask it will be 49. Then, all elements are summed and this sum is then divided by the previously calculated number of center cells. The result obtained is used to form a mask in the upper branch of the filter. The original mask is subtracted from this mask, and as a result, the required values in the cells are obtained, the sum of which is equal to the sum of the outer area of the mask.

Also, the modified filter must be supplemented with two coefficients, the values of which are set at the input. The first coefficient in the process of implementing the final mask raises the central mask by n values, and the second coefficient subjects the central element of the entire mask to the same operation.

The reactions that should be formed by the filter-rum are presented in tab. 1 on the example of variation in the values of the coefficients of the recirculators, the size of the internal mask, the recirculators for its convolution and the values of its shift in cases of given mask sizes from 3×3 to 17×17.

Tab. 1. Dependence of filter indicators on changing the mask size

Target aperture size	Ratio LR and FR	Inner mask size	LR and FR for inner mask	Inner mask shift factor
3×3	3 and 1	1×1	1 and 1	2
5×5	4 and 2	1×1	1 and 1	3
7×7	5 and 3	3×3	3 and 3	3
9×9	6 and 4	3×3	3 and 3	4
11×11	7 and 5	5×5	5 and 5	4
13×13	8 and 6	5×5	5 and 5	5
15×15	9 and 7	7×7	7 and 7	5
17×17	10 and 8	7×7	7 and 7	6

However, when trying to conduct experiments on the formation of masks of dimensions 11×11 and more, that is, the inner mask, which becomes more than 3×3, it turns out that the masks at the output do not meet the “truncated” conditions. The mask in its three-dimensional representation should resemble a truncated pyramid in shape, however, masks larger than 9×9 have a dip in the center, which makes it impossible to use them as “truncated” pyramid masks.

From this follows the conclusion that the original algorithm for generating masks is not suitable for dimensions of 11×11 and higher. Therefore, for the correct fulfillment of the set goal, it is necessary to develop a new block diagram.

To implement a mask, the inner part of which has a dimension of 5×5 or more, the following algorithm is implemented. First, a mask is formed in the lower branch, as in the previous version, of a given dimension and the corresponding coefficients of the line and frame recirculators.

Then, in the second branch of the filter, a second mask is formed, LTP of the same dimension as the inner mask from the lower branch. At the same time, it is necessary to determine the coefficient that will be fed to this branch, and with which convolution will occur by line and personnel recirculators. This mask is similar to the upper branch of the first version of the modification, but differs in the type of convolution. Instead of convolving with one frame and one line recirculator with the same values, as a result of which a homogeneous mask is formed, in this case, two line and two frame recirculators are convolved, as a result of which the mask will take on a form different from a homogeneous mask.

The resulting mask is summed with the first mask (the main one), but the result will not have a sum of elements equal to zero. For this reason, an additional branch appears in the filter, the third one, it performs a similar function as the upper branch of the original filter, that is, it creates a uniform 3×3 mask filled with certain numbers. This value must also be calculated depending on the missing difference up to an amount equal to zero.

In each case, when the specified mask size implies an increase in the central mask (5×5 for 11×11, 7×7 for 15×15, etc.), the mask formed in the second branch also increases. However, the third mask, which is homogeneous, always remains unchanged, since the truncation of the pyramid always has a dimension of 3×3. The final block diagram of the LTP adaptive filter is shown in Fig. 3, where , $x(n_1,n_2)$ – input data, $y(n_1,n_2)$ – output data, D – coefficient for additional mask convolution; a – additional mask shift factor; m_1 – coefficient of line and frame recirculators for additional mask; d_1 and d_2 – line and frame recirculator coefficients for the main mask; F – к coefficient for 3×3 mask convolution; b – mask shift factor 3×3; c – offset factor for the magnification mask of the central element; A_1 – lifting coefficient of the central aperture of the final mask; A_2 – magnification factor of the central element.

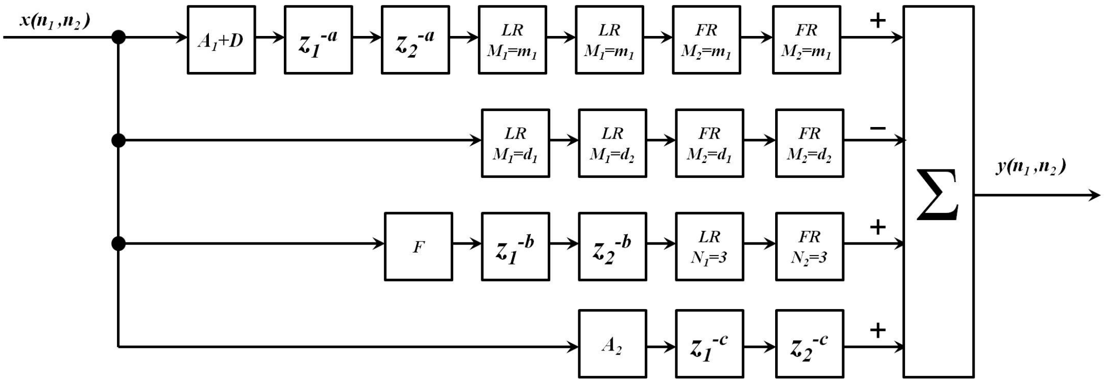

Fig. 3. Structural diagram of the modified LTP filter

These changes also affected the number of required coefficients. A number of values necessary for the formation of the final mask appeared. Accordingly, the reactions listed above, including new additions that should be formed by the filter, are presented in tab. 2 on the example of some values. Among them are the values of the coefficients of line and frame recirculators of the main mask, the size of the internal mask, its line and frame recirculators, its shift coefficients, as well as the shift of the third additional mask and the shift of the central element, in cases of given mask sizes from 7×7 to 17×17 .

Tab. 2. Added dependence of filter indicators on changing the mask size

Specified size	Coef. LR and FR	Inner mask size	LR and FR for inner mask	Coef. inner mask shift	Coef. mask shift 3×3	Coef. Shift central element
7×7	5 and 3	3×3	3 and 1	3	4	3
9×9	6 and 4	3×3	3 and 1	4	5	4
11×11	7 and 5	5×5	4 and 2	4	6	5
13×13	8 and 6	5×5	4 and 2	5	7	6
15×15	9 and 7	7×7	5 and 3	5	8	7

3. Modification of the LDP filter construction algorithm

Similar to the "truncated" pyramid Laplacian filter, in its basic representation the filter generates a 7×7 mask and must undergo similar modifications to achieve adaptability.

The basis of the final mask is a 7×7 matrix generated in one of the branches due to the coefficients of the line and frame recirculators. The values given in them serve to form the size of the mask, and their value, respectively, affects either the final matrix. Accordingly, for the size 7×7, which is an option for the basic version of the filter, two line recirculators with coefficients of 5 and 3 and two vertical recirculators with coefficients of 5 and 3 are used.

To create the adaptability of this filter, it is necessary first of all to model the response of the filter to a given dimension value. In this case, work occurs exclusively with odd values (9×9, 11×11, 13×13, etc.). For this purpose, the sensitivity of the coefficients of the recirculators to the values specified by the user is implemented depending on 1/2. This means that changing the value of the filter size (always by 2 to preserve oddness) adds one to each coefficient of the recirculators. In this case, with a given dimension of 9×9, the coefficients of the line and frame recirculators will be equal to 6 and 4, and with a dimension of 11×11 – 7 and 5.

However, in the other branch of the filter, a mask smaller than 7×7 is generated. This is the central mask, which will later serve to create positive elements in a certain area inside the main mask in the presence of a border in the form of negative ones. This is necessary to normalize the brightness. However, we can conclude that with an increase in the size of the mask, it is advisable to ensure the reaction of the size of its center. Given the ratio of the central mask to the outer “rings”, the most appropriate option for maintaining it would be to start the process of increasing the mask every other time, that is, every time the mask is doubled. In this case, the central 3×3 mask will remain at the given size of 7×7 and 9×9, but expand by one cell to 5×5 at the dimensions of 11×11 and 13×13. For this purpose, the sensitivity of the coefficients of the recirculators of the upper branch of the filter to the values specified by the user is implemented. That is, every second possible value of the mask size, starting from 3×3, will change the size of the inner mask.

However, in addition to line and frame recirculators, the creation of a correct mask in a given branch of the filter is also affected by the shift coefficients. And since changing the filter dimension also affects the position of the mask generated in the upper branch, provided that it must always be in the center of the main mask, it is necessary to provide a filter response in circuit elements z_1 and z_2. With a standard dimension of 7×7, the upper left corner of the central mask is located on the $x(n_1-1, n_2-2)$ cell. After some analysis, it follows that every second of the possible mask size values, starting from 5×5, will change the shift factor of the internal mask by 1. So, for example, at 5×5 the shift will have a value of 2, as well as at 7×7 (not 1, since the size of the inner mask will also shrink by 1 cell and take on a size of 1×1). When the size of the main mask is 9×9 and the inner one, respectively, 3×3, the shift will increase to 3.

In code, this process can be represented by some equation using the indicators of the size of the matrices. The shift factor of the inner mask will be equal to the value obtained by subtracting the size of the inner mask from the given size of the general mask, and divided by two. So, for example, with a given size of 11×11, it will turn out: $(11-5)/2=3$. Therefore, the matrix is shifted by -3.

The coefficient 14 in the same branch serves to increase the positive branch of the filter and ensures the correct ratio of the sums of the inner and outer parts of the final matrix, that is, it allows you to get the sum of the coefficients equal to zero. So, with a mask size value of 7×7, the inner part of the mask was a 3×3 cell. The sum of its internal coefficients was 81, when the sum of the two outer “rings” of the mask is 144. As a result, the total sum of all matrix elements is 224. Since the mask is fed to the adder with a negative sign, the sum of the elements of the inner mask will be equal to -81, and the outer -144. Accordingly, in order to achieve the value of the sum of the inner mask, which is opposite in sign to the sum of the outer one, that is, 144, it is necessary to add a total value of 224 to the inner mask (because $81+144=224$). That is, the same sum of all elements of the matrix. To achieve this result, it is necessary to determine one number, which, when folded in the inner mask, gives a sum equal to the sum of all elements of the mask. In this case, this number turned out to be 14 (because $244/16=14$). The value 16 in this case is the sum of the elements in the convolution of the value 1 and in some way denotes the number of "ones", the original coefficients for the convolution, which are in the internal matrix. However, it is only suitable for aperture sizes of 7×7 and 9×9, as it is the result of calculating the sum of a 3×3 matrix.

The same should happen with inner masks of other sizes. To begin with, the summation of all elements is performed and the subsequent division of this sum by the previously calculated sum of the cells of the center. As a result, it gives a coefficient, which is subsequently used to form a mask in the upper branch of the filter. The original mask is subtracted from this mask, and as a result, the required values in the cells are obtained, the sum of which turns out to be equal to the sum of the outer area of the mask. Accordingly, with an increase in the size of the aperture, not only the desired value of the coefficient for convolution should be calculated, but also an additional value for finding it.

Also, the modified filter must contain the same optional functions as in the modification of the Laplacian "truncated" pyramid. We mean the implementation of two coefficients, the values of which are given at the input. The first coefficient in the process of forming the final mask raises the central mask by n values, and the second coefficient subjects the central element of the entire mask to the same operation.

All the reactions listed above, which should be formed by the filter, are presented in Table. 3 on the example of an overview of the values of the coefficients, the size of the internal mask and its shift in cases of given mask sizes from 7×7 to 17×17.

Tab. 3. Dependence of filter indicators on changing the mask size

Specified size	Coefficient LR and FR	Inner mask size	Inner mask shift factor	LR and FR for inner mask
7×7	5 and 3	3×3	3	2 and 2
9×9	6 and 4	3×3	4	2 and 2
11×11	7 and 5	5×5	4	3 and 3
13×13	8 and 6	5×5	5	3 and 3
15×15	9 and 7	7×7	5	4 and 4
17×17	10 and 8	7×7	6	4 and 4

Based on the foregoing, the filter undergoes a number of changes and takes the following form, shown in Fig. 4, where $x(n_1, n_2)$ – input data, $y(n_1, n_2)$ – output data, D – coefficient for additional mask convolution; a – additional mask shift factor; m_1 – coefficient of line and frame recirculators for additional mask; d_1 and d_2 – line and frame recirculator coefficients for the main mask; c – кoffset factor for the center element magnification mask; A_1 – central aperture elevation factor; A_2 – magnification factor of the central element.

4. Experimental study of the dependence of the aperture size on the processing time

In the framework of this work, it is necessary to experimentally confirm not only the speed of these adaptive filters, but also to investigate the dependence of the processing time on the size of the filter aperture. The platform for the experiments is the MATLAB software, and the classical two-dimensional convolution (CTC) filter is used as a comparison filter.

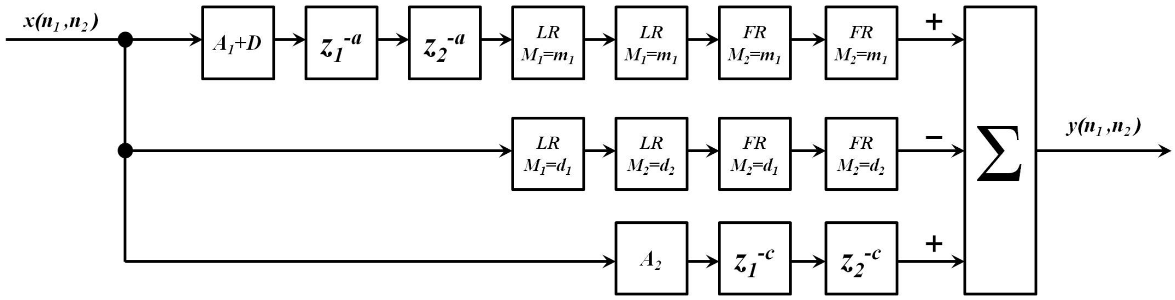

Fig. 4. Structural diagram of the modified LDP filter

To carry out these experimental studies, three images of different dimensions are used. Among them are images of dimensions 640×480, 1920×1080 and 5472×3078.

The study is based on the evaluation of the performance of convolution of image data by classical two-dimensional convolution, developed by the adaptive modified LTP filter and the adaptive modified LDP filter. Accordingly, to assess the dependence of the aperture size and speed, each image is subject to convolution with different aperture sizes, namely 7×7, 9×9, 11×11, 15×15, 25×25 and 49×49.

4.1. Study of the 640x480 image filtering process

In the first block of the experiment, work is performed with the first image, it has a dimension of 640×480 and a tif format. In the first stage of working with it, it is subjected to convolution with a 7×7 mask. The measurement results are presented in Tab. 4.

Tab. 4. Measurement results for 640×480 image

	Aperture size	Function	№ experiment										
			1	2	3	4	5	6	7	8	9	10	Σ/10
Processing time, s	7×7	CTC LTP	0.633	0.635	0.630	0.615	0.607	0.638	0.703	0.621	0.652	0.645	0.638
		LTP	0.189	0.186	0.173	0.213	0.169	0.183	0.175	0.189	0.181	0.176	0.183
		CTC LDP	0.577	0.605	0.575	0.558	0.612	0.593	0.639	0.615	0.609	0.620	0.6
		LDP	0.137	0.142	0.136	0.147	0.147	0.148	0.144	0.137	0.150	0.136	0.142
	9×9	CTC LTP	0.797	0.763	0.824	0.684	0.649	0.653	0.734	0.726	0.755	0.669	0.712
		LTP	0.196	0.207	0.192	0.196	0.180	0.191	0.207	0.216	0.194	0.180	0.195
		CTC LDP	0.764	0.785	0.756	0.690	0.610	0.641	0.697	0.678	0.720	0.646	0.68
		LDP	0.165	0.158	0.198	0.146	0.138	0.138	0.154	0.150	0.155	0.148	0.153
	11×11	CTC LTP	0.667	0.720	0.764	0.739	0.760	0.756	0.766	0.771	0.785	0.782	0.751
		LTP	0.199	0.213	0.188	0.191	0.181	0.184	0.182	0.192	0.210	0.190	0.193
		CTC LDP	0.714	0.760	0.716	0.677	0.722	0.724	0.692	0.750	0.809	0.697	0.726
		LDP	0.142	0.165	0.140	0.146	0.151	0.149	0.169	0.136	0.142	0.145	0.149
	15×15	CTC LTP	0.799	0.877	0.832	0.818	0.804	0.834	0.814	0.789	0.803	0.900	0.827
		LTP	0.191	0.193	0.196	0.193	0.192	0.198	0.190	0.200	0.196	0.205	0.195
		CTC LDP	0.775	0.865	0.802	0.764	0.797	0.795	0.773	0.744	0.798	0.868	0.798
		LDP	0.156	0.148	0.141	0.164	0.150	0.153	0.145	0.186	0.156	0.157	0.156
	25×25	CTC LTP	1.028	1.194	1.182	1.159	1.056	1.205	1.079	1.015	1.086	1.082	1.109
		LTP	0.193	0.194	0.219	0.171	0.178	0.173	0.186	0.193	0.234	0.200	0.194
		CTC LDP	1.020	1.090	1.148	1.091	1.068	1.070	1.051	1.037	1.057	1.002	1.063
		LDP	0.150	0.146	0.142	0.140	0.139	0.182	0.139	0.156	0.194	0.137	0.153
	49×49	CTC LTP	2.579	2.491	2.580	2.698	2.838	2.563	2.658	2.471	2.362	2.414	2.565
		LTP	0.191	0.178	0.181	0.248	0.192	0.179	0.196	0.181	0.193	0.187	0.193
		CTC LDP	2.463	2.406	2.256	2.888	2.475	2.207	2.364	2.293	2.286	2.194	2.383
		LDP	0.157	0.147	0.147	0.171	0.173	0.147	0.162	0.151	0.153	0.150	0.156

When analyzing the results obtained for a 7×7 mask, it is noticeable that the constructed adaptive filters are faster than the classical convolution. So, when working with MATLAB function algorithms, the adaptive filters LTP and LDP outperform classical convolution by 3.48 and 4.22 times, respectively, in terms of speed. With an aperture size of 9×9, the adaptive filters LTP and LDP outperform classical convolution by 3.7 and 4.51 times, respectively. With a mask of 11×11, the adaptive filters LTP and LDP outperform classical convolution by 3.89 and 4.89 times, respectively. With a mask of 15×15, the adaptive filters LTP and LDP outperform classical convolution by 4.23 and 5.13 times, respectively. With a mask size of 25×25, the adaptive filters LTP and LDP outperform classical convolution by 5.71 and 6.98 times, respectively. With a size of 49×49, the adaptive filters LTP and LDP outperform classical convolution by 13.83 and 15.30 times, respectively. According to Table. Fig. 4 plots the dependence of speed on the size of the aperture (Fig. 5).

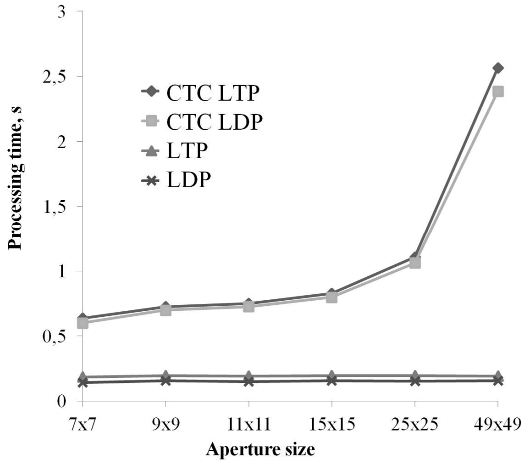

Fig. 5. Graph of the dependence of performance on the size of the aperture when processing an image of 640×480

4.2. Study of the 1920×1080 image filtering process

Similarly to the experimental technique in paragraph 4.1, we will conduct a study for an image with a dimension of 1920×1080 and a bmp format. Let's give average values of measurement of processing time presented in Tab. 5.

Tab. 5. Average image processing time 1920×1080

Aperture size	Processing time, s			
	CTC LTP	LTP	CTC LDP	LDP
7×7	3.938	0.721	3.789	0.599
9×9	4.401	0.778	4.266	0.671
11×11	4.678	0.742	4.321	0.596
15×15	5.252	0.833	5.133	0.666
25×25	6.381	0.730	6.252	0.601
49×49	15.127	0.829	15.285	0.667

When analyzing the obtained results, it is noticeable that the constructed adaptive filters are faster than the classical convolution. Adaptive filters LTP and LDP outperform classical convolution in speed: with a size of 7×7, 5.47 and 6.32 times, respectively; with a size of 9×9 by 5.66 and 6.36 times, respectively; with a size of 11×11 by 6.30 and 7.25 times, respectively; with a size of 15×15 by 6.3 and 7.71 times, respectively; with a size of 25×25 by 8.75 and 10.4 times, respectively; with a size of 49×49 by 18.24 and 22.93 times, respectively. According to Tab. 5 plot the dependence of performance on the size of the aperture when processing an image with a size of 1920×1080, shown in Fig. 6.

4.3. Study of the image filtering process 5472×3078

In the third block of the experiment, work is performed with the third image, it has a dimension of 5472×3078 and a jpg format. The average processing time for the third image is presented in Tab. 6.

When analyzing the obtained results, it is noticeable that the constructed adaptive filters are faster than the classical convolution. So, when working with MATLAB function algorithms, the LTP and LDP adaptive filters outperform the classical convolution by 5.33 and 7.07 times for a 7×7 mask, by 5.86 and 7.36 times for a 9×9 mask, by 6.33 and 7, 58 times for an 11×11 mask, 6.74 and 8.82 times for a 15×15 mask, 8.5 and 10.87 times for 25×25, 18.99 and 23.88 times for a 49×49 mask. According to Tab. 6 plot the dependence of performance on the aperture size when processing an image with a size of 5472×3648 (Fig. 7).

Tab. 6. Average values of image processing time 5472×3078

Aperture size	Processing time, s			
	CTC LTP	LTP	CTC LDP	LDP
7×7	34.466	6.471	34.479	4.877
9×9	37.165	6.495	35.102	4.869
11×11	36.019	5.691	35.416	4.672
15×15	41.912	6.220	41.592	4.714
25×25	54.640	6.425	53.935	4.964
49×49	114.241	6.017	113.447	4.751

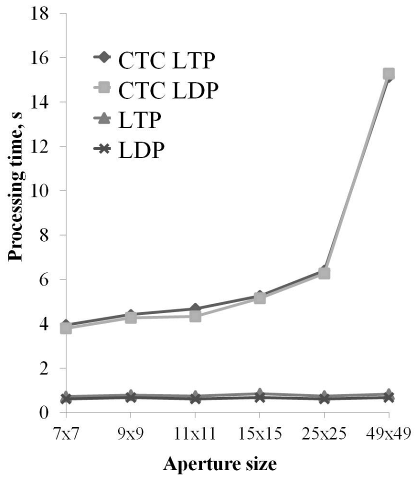

Fig. 6. Graph of the dependence of performance on the size of the aperture when processing an image of 1920×1080

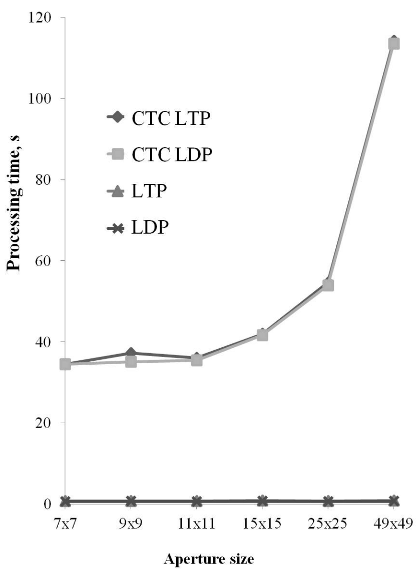

Fig. 7. Graph of the dependence of performance on the size of the aperture when processing an image of 5472×6348

5. Application of the developed algorithms

The proposed LTP and LDP filters are a modification of two-dimensional Laplace filters. They are also filters that increase the clarity of images and are responsible for separating small-sized objects from the background component. Let's demonstrate this in a visual experiment to increase the clarity of images.

To conduct experimental studies to determine the optimal coefficients for the developed filters, a test image was taken, obtained using an active-pulse television measuring system. During the experiment, the value of the coefficients *A* changed in the selected filters. In the case of a change in the central aperture of a 3×3 element, the coefficients A_1 and A_3 were used; in the case of lifting the central element, the coefficients A_2 and A_4 were used.

The resolution of the processed images was estimated in the number of television lines (TVL), the measurement was carried out using specialized software Imatest.

The results of measuring the resolution of images after processing by the LTP filter are shown in Tab. 7, for the variant with the rise of the central aperture of the 3×3 element, the filtration coefficient was $A_1 = 3$, and for the variant with the rise of the central element, the coefficient $A_2 = 14$.

Tab. 7. Results of processing by the LUP filter

Aperture lift 3×3 elements		Raise the center of the mask	
Coef. A_1	TVL	Coef. A_2	TVL
original	201.6	original	201.6
1	1051.2	13	763.2
2	*518.4*	*14*	*633.6*
3	403.2	15	590.4
4	360	16	561.6

The results of processing when implementing the LDP filter are shown in Tab. 8, in the case of raising the central aperture of a 3×3 element, the coefficient $A_3 = 2$, as well as for the LTP filter, when the central element is raised, the coefficient $A_4 = 16$.

Tab. 8. Results of processing by the LDP filter

Aperture lift 3×3 elements		Raise the center of the mask	
Coef. A_3	TVL	Coef. A_4	TVL
original	201.6	original	201.6
1	1209.6	15	1195.2
2	*590.4*	*16*	*691.2*
3	489.6	17	648
4	403.2	18	619.2

On Fig. 7 shows graphs of contrast-frequency characteristics (CFC) of images after processing with recursively separable filters. For a visual assessment of the effectiveness of the algorithms, we present fragments of the processed images in Fig. 8.

Conclusion

When analyzing the results of experimental studies, it can be concluded that with an increase in the image size, the time required for computational operations increases. However, when processed by adaptive filters using recursively separable algorithms, this growth is almost imperceptible. In the experiment with the first image with an aperture size of 7×7, the filters completed the work in an average of 0.19 seconds, in the second - in an average of 0.73 seconds, and with the third, largest of the test images, the filters took an average of 6.5 seconds. This increase in processing time is negligible compared to the increase in processing time for classical 2D convolution. So, with an aperture size of 7×7, for the first image it processed in an average of 0.64 seconds, for the second image in an average of 3.9 seconds, and it took 34.5 seconds to process the third image.

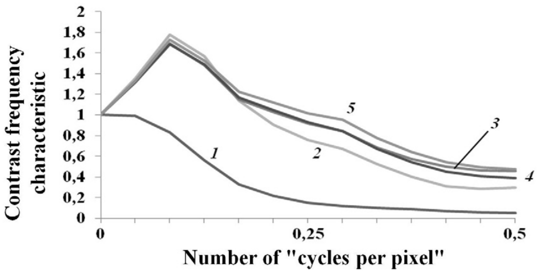

Fig. 8. CFC graphs: 1 – original image; 2 – LTP aperture rise 3×3, A_1=2; 3 – LTP lifting of the central element, A_2=14; 4 – LDP aperture rise 3×3, A_3=2; 5 – LDP lifting of the central element, A_4=16

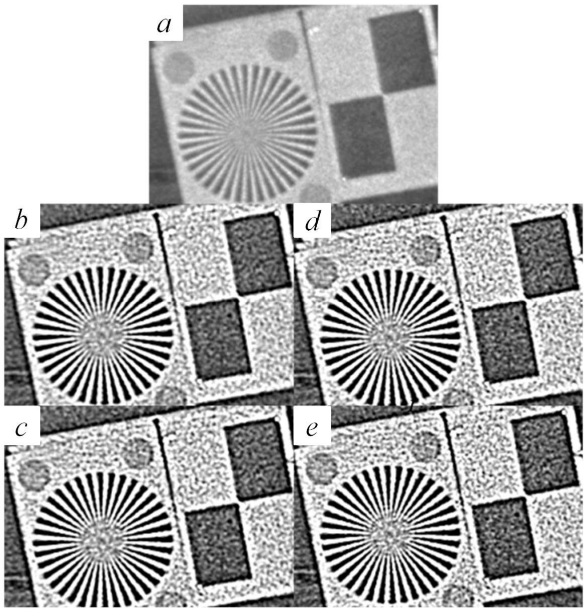

Fig. 9. Fragments of the test image. a) original image; b) LTP – aperture rise 3×3; c) LTP – lifting of the central element; d) LDP – aperture rise 3×3; e) LDP – lifting of the central element

This performance is not optimal, in contrast to the performance of adaptive recursively separable filters. One of the main and most important reasons is the need to increase the size of the aperture, which, as can be seen from the results of an experimental study, has a significant impact on the speed of classical two-dimensional convolution. Whereas the time required for processing by adaptive recursively separable filters varies on average with one value of a topology-defined two-dimensional recursively separable digital filter.

The paper demonstrates the effectiveness of the developed algorithms in improving the clarity of images. Efficiency is shown with different approaches to changing the filtration coefficients.

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