Methods and algorithms for contour analysis of optical and infrared images

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The report is devoted to the synthesis of algorithms for optical image processing (contours of image), for forming recognized indicators that are used to solve the problems of recognition of cosmic objects, in particular, in the problems of the selection of structural elements of observed objects, as well as combining individual images.

The advantage of the methods of contour analysis in the problems of image processing is the ability to solve them from unified theoretical positions, and program implementation of the synthesized algorithms in an automatic mode. The ignorance of options, positions, rotations, and scale of images has little effect on the amount of computation.

A model, describing the contour of the object as an approximation to the structure,of a closed polygon of the corresponding order was proposed. Synthesized compression algorithms and equalization outlines were used to solve this problem.

A quantitative scalar form factor was introduced. This is invariant to transformations of scaling and rotation of the contour in the plane, the shift of its initial position and displacement of the image on the frame.

To determine the potential for the selection of structural elements in the images of objects by contour analysis methods, a numerical study of the parameters of regular polygon shapes up to 6th order and second-order figures was carried out.

An algorithm for matching the images of the object obtained on different frames, using the distinguished contours of objects, was proposed.

Earlier in one of the papers / 6 / on the basis of the spatial matched filter, a synthesized algorithm for separating the image of the space object of an unknown form under the background was presented; the probabilistic characteristics are unknown a priori.

The problem may be solved automatically. The key information processing is the outline of the object.

The advantage of the method of contour analysis in the problems of image processing is the ability to address them from unified theoretical positions, and the software implementation of the synthesized algorithms for automatic operation. In this case, ignorance of position, rotation, and scale of the images of the space object of interest has little effect on the amount of computation.

The report focuses on the synthesis of algorithms for filtering the contour forming on them as indicators of the recognition (IR) used to solve the problems of recognition of space objects, particularly in the problem of the structural elements of the observed objects and the algorithm for combining individual images.

Approximation of a contour by a closed polygon

As the mathematical model of the contour was chosen, a contour signal model is a set of sequences of complex vectors, the coordinates of each vector on the plane are relative to the end of the previous one. The start position of the first is selected as the origin. The contour is closed, that is, the direction of circumvention (clockwise or counterclockwise) is set, and moving about elements of the contour, we get back to the start point. The transition from the current point to the next available in eight directions, four of which are in straight lines, and four - on a diagonal. By introducing a complex description of the locations of the cells on the plane, at each step of apportionment of the next point of the contour, we assume that the origin coincides with the position of the selected point in the previous step. We choose a model for the description of the contour signal as its representation on the plane, with the help of a complex variable. Then, the position of the neighboring pixels is defined by eight standard elementary vectors (EV), whose coordinates are represented by the following matrix

$$\begin{Vmatrix} -1+j & j & 1+j \\ -1 & 0 & 1 \\ -1-j & -j & 1-j \end{Vmatrix}.$$

Setting the direction of the circuit of adjacent pixels in a clockwise direction, and beginning a bypass from the upper left cell, we write the contour in the form of

$$\Gamma(n, E) = \Gamma(e(k)_i, i = 0, \dots, n-1);\ k = 0 \div 7$$

Then, group the set of neighboring pixels, the transition to which is in the same direction.

Subsequently the model describing the contour signal is next received as representation on the plane

$$\Gamma(n,Z)=\Gamma(z_i, i=0,\ldots,n-1);\ where\ z_i = x_i + jy_i\ or\ z_i=(\rho_i,\varphi_i);\ j=\sqrt{-1}.$$

Here $\Gamma(n,Z)$ - the contour containing n complex vectors, the description of which can be set in rectangular or polar coordinates. The parameter n is called the order of the circuit / 4 /. Each vector connects two adjacent vertices of the restored contour.

For the closed path the equality is $\sum_{i=0}^{n-1} z_i = 0,$

For comparison with the contours of the same order, we assume that they are elements of a suitable space, in which a metric L_2 is determined.

In this case, according to / 4 / a measure of closeness in the metric L_2 can be entered in the space of the contours of the same order (the number of units of the polygon outline). The corresponding scalar, $\alpha(\Gamma,\Gamma')$, product, and the distance, ρ between the two contours are given by

$$\alpha(\Gamma,\Gamma')=\langle\Gamma(n,Z)\,|\,\Gamma'(n,Z)\rangle=\sum_{i=0}^{n-1} z_i z_i';\quad \Delta(\Gamma,\Gamma')=\Gamma(n,Z)-\Gamma'(n,Z);$$

$$\rho^2=\langle\Delta(\Gamma,\Gamma')\,|\,\Delta(\Gamma,\Gamma')\rangle$$

where $\Gamma(n,Z)$ – declaration of contour, n – its order Z – n-th complex vector of its coordinates.

For use of the proposed description in the synthesis of algorithms for contour analysis, an orthonormal basis of contours in the family of contours selected order n should be introduced. The complex vector scalar product operation is defined, it can be constructed using the procedure for Gram-Schmidt orthogonalization in the presence of n linearly independent contours. Alternative path - use as a basis the set of elementary contours (EC) $\{\Gamma(n,\rho)\}$, the i-th base contour is determined by the relation

$$\Gamma_i(n)=|\rho|\exp\{-2\pi jik/n\},\ k=0,\ldots n-1.$$

EC are contours those that look on a plane like properly oriented n-gons with the same length of edges and angles between the adjacent vectors, which are equal in magnitude and equal $2\pi i/n$. The relation holds, $\langle \Gamma_i(n,\rho) \mid \Gamma_u(n,\rho) \rangle = |\rho|^2 n\delta_{iu}$. We assume that the parameter ρ is chosen such that the basis is orthonormal, and we shall omit it in the notation.

We will now describe some contour processing algorithms within the selected models of their mathematical description.

Equalization algorithm (compression) of the contour

When working with noisy vectors in problems of comparison contours, it's needed to equalize order contours. The alignment procedure of dimensional contours is called equalization.

We describe an algorithm equalization that implements the process of reducing the dimension of the original contour. The quasicontour $\Gamma(n,Z')$ is built on the initial contour $\Gamma(n,Z)$. Each vector is the sum of two consecutive vectors of the original, and combines the i-th and i +2- th points.

$$z'_i = z_i + z_{i+1}, i = 0,\ldots,n-1.$$

The built quasicontours are closed for an odd order of the initial contour, or consist of two closed loops for even order. The order quasicontour is the same order as the source. When n = 3, the direction of the contour units quasicontour is opposite to the bypass links of the initial contour. The process of equalization can be done as long as the order of the circuit is reduced to three.

A set of triangles formed by two adjacent vectors of contour $\Gamma(n,Z)$ and vector of $\Gamma(n,Z')$ is built.

The areas of triangles S_i $i = 1,\ldots,n.$, built on two adjacent links of the original contour, is found by calculating their vector product

$$S_i = \left\| \left[Z_i, Z_{i+1} \right] \right\|.$$

Exclude from the initial contour the peak associated with the minimum value S_i. The two corresponding vectors are removed from the contour. A closed contour is formed by adding to it a vector of quasicontour found associated with the vertex of the initial contour. This vector is removed from quasicontour, and the state vectors coming off and coming in the remote top of the contour $\Gamma(n,Z)$ are adjusted. Thus, a new path $\Gamma(n-1,Z)$ with the new state vector z_i is created, and index vectors, whose numbers exceed i are decremented.

In the following steps only the areas of triangles containing the newly formed link polytope are evaluated.

A subsequent removal of the vectors is produced according to the above described algorithm.

Form of a flat object and the algorithm of its formation

An analytical determination of the shape of the contour is made.

In the image processing algorithms and, in particular, their contour analysis is a widely used concept of form. The analytical determination of the shape of the object must have the proximity metric properties needed when comparing images of contours objects on the proximity of the two forms of the images.

There is no generally accepted definition of the form. One of the requirements to the scalar characteristic form F is to ensure the invariance of its value to the selected transformation group G of the source image S and / or the its contour Γ

$$\Phi = \inf S_G = \inf \Gamma_G .$$

As a group of transformations we choose a group of linear transformations, which includes the following set of parameters $\{\mu, d, h\}$, where $\mu = |\mu| \exp\{-j\Delta\varphi\}$ - in the time scale transformation, and turning by a corner $\Delta\varphi$; d parameter shift of the starting point of the contour; $h = h_x + jh_y$ - shifts the image horizontally and vertically.

The solution of the difference between the two forms is based on finding the minimum distance between them, when you change the values of the parameters transformation, G. The solution can be implemented in the following manner.

- Contour of the image is formed $\{\Gamma(n, \rho)\}$
- Vector, having a maximum length is selected

- Start contour is aligned with the beginning of the selected vector
- Contour is normalized and rotated so that the found vector would be horizontal and directed to the right
- In / 4 / the coefficient simplicity of the form (or form factor) η is put, which is calculated by the formula

$$\eta = 1 - \frac{\rho_{\max}}{\|\Gamma(n,Z)\|}\sqrt{\frac{n}{(n-1)}}$$

This factor varies in the interval (0,1), and the higher it is, the simpler the form.

Carrying out the above transformation allows evaluating the parameter μ, when comparing the contours of two successive pictures of a selected object.

The algorithm for generating indicators of recognition

The problem of recognition is understood to be a wide class of problems, which are based on hypothesis testing algorithms, possibly with simultaneous evaluation parameters.

In an analysis of the image, a remote space object can be solved by the next class of recognition tasks:

to determine to which class the observed spacecraft is (selection problem)

to highlight important structural elements inherent to the spacecraft (eg, antennas, solar panels, rods, etc.)

to estimate the size of the items found and establish the fact of a change in their condition (e.g., orientation, rotation, failure, etc.).

An important issue is the fact that for the solution of the mentioned problems, it is necessary to carry out the analysis in the presence of nuisance parameters.

One way to obtain a stable solution of the problems of recognition is to find informative and stable conditions of observation indicators of recognition (IR), providing a high-quality solution of the problems of recognition of interest in a given class of space objects (alphabet). Unfortunately, with the recognition of spacecraft in its image, one cannot provide a complete alphabet. However, analysis of the population of projections on the plane of the designs of spacecraft shows that in the majority of cases they can be limited to the following set of simple shapes, the combination of which forms an image of the object.

- Figures like straight lines or elongated rectangles, inherent projections of rods or rod antennas.
- Triangles of different configurations resulting from composite structures of space objects of conical shape.
- Rectangles, involved, as a rule, with projections of solar panels.
- Regular polygons, a number of faces that do not exceed six.
- The figures of the second order, or their parts, the simplest form of those is a circle. The presence of such figures on the images is associated with the imagery of antennas of various designs.

One path to search for informative IR is to create them using the contour analysis. One possible combination of IR, we can choose a set of coefficients simply of the form $\eta(k); k = n, n-1, \ldots, 3.$ The algorithm of their formation is the following.

- The initial contour of the image is selected.
- The maximum value of the order of the contour n is found, and the form factor is calculated.
- By grouping elementary vectors, theinitial description of the contour is constructed and the appropriate form factor is calculated.
- A consistent equalization of the contour is realized, as long as the parameter of contour becomes equal to three.
- For each value of n the form factor is calculated.

A set of the images makes the vector IR$|\eta\rangle$. The formed vector is invariant under the group of transformations G. So it can be used both in the learning process of the recognition algorithms, and in the formation of the decision rule.

We have conducted studies to determine the potential for solving the allocation of the structural elements of space objects based on their contours of a given order. An estimated parameter is the minimum size defined of a number of pixels, in which it may be the sustained selection of the contour of the circle of the appropriate size.

Results of the study of the possibilities of using a contour representation of images to solve problems.

We now turn to the main results of the research of the possibilities of using the selected vector IR, whose components are the coefficients of the contour form of the corresponding order. The study is focused on assessing the potential of determining the geometric shape of the projection of the structural elements on the picture plane, and the impact of digitization of the received images to determine the geometry in relation to the circle, as the worst figures of the number of pieces of a simple form in terms of the recognition of a regular polygon.

Analysis of the behavior the form factor of the triangles

Consider first the right triangles. The corresponding dependence on the size of the acute angle is shown in Fig. 1.

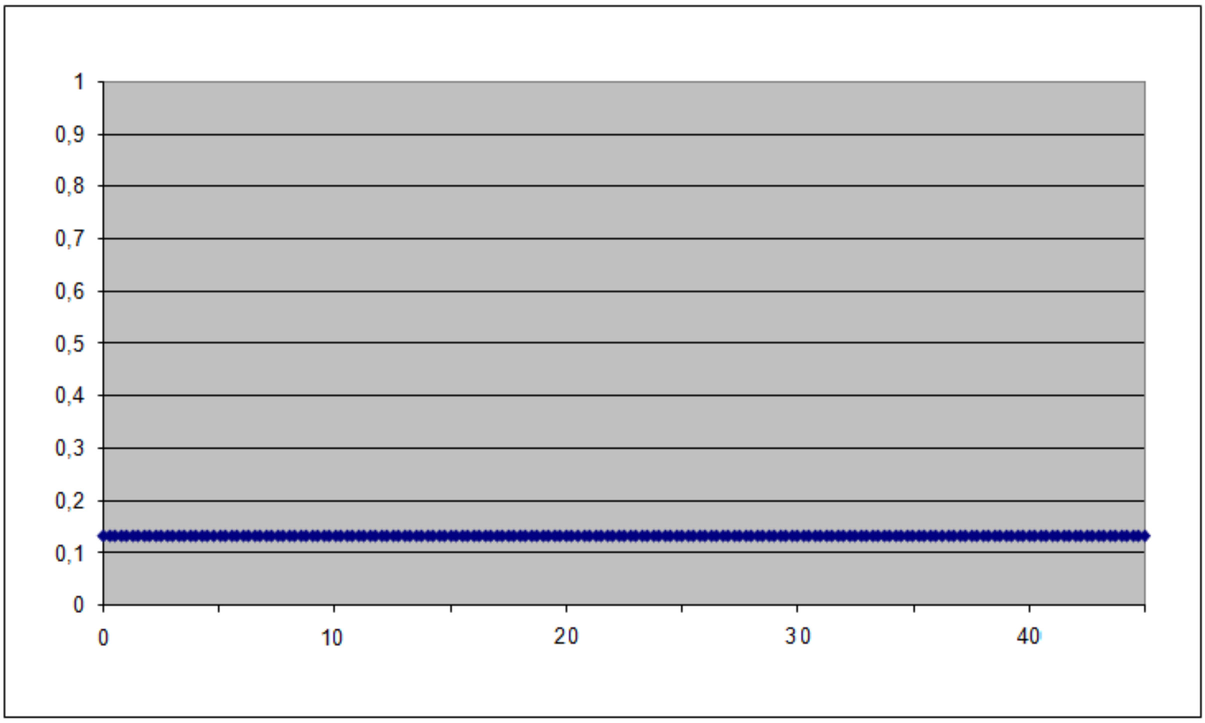


Fig. 1. Form factors of right triangles

From the analysis of the dependence of the form factor it can be concluded that the coefficient η≈0.134 is an invariant for this class of triangles, and can be used as a IR in the allocation of the picture elements of a design as plates and / or solar panels.

The complete set of relationships for all triangles, in which an acute angle in steps of 10° is selected as a parameter, is shown in Fig. 2. It should be noted that in this case, to make a definitive decision about the geometry of the shapes, a single value of the form factor is not possible. But it can be emphasized there are two patterns in the behavior of the curves.

The first of these is to achieve twice the value η, equal to the value of a right triangle. In the first case (due to the particular implementation of the algorithm computing), the corresponding triangle degenerates into a rod, in the second we have a true right triangle.

The maximum value of the form factor η≈0.293 is attained for the equilateral triangle.

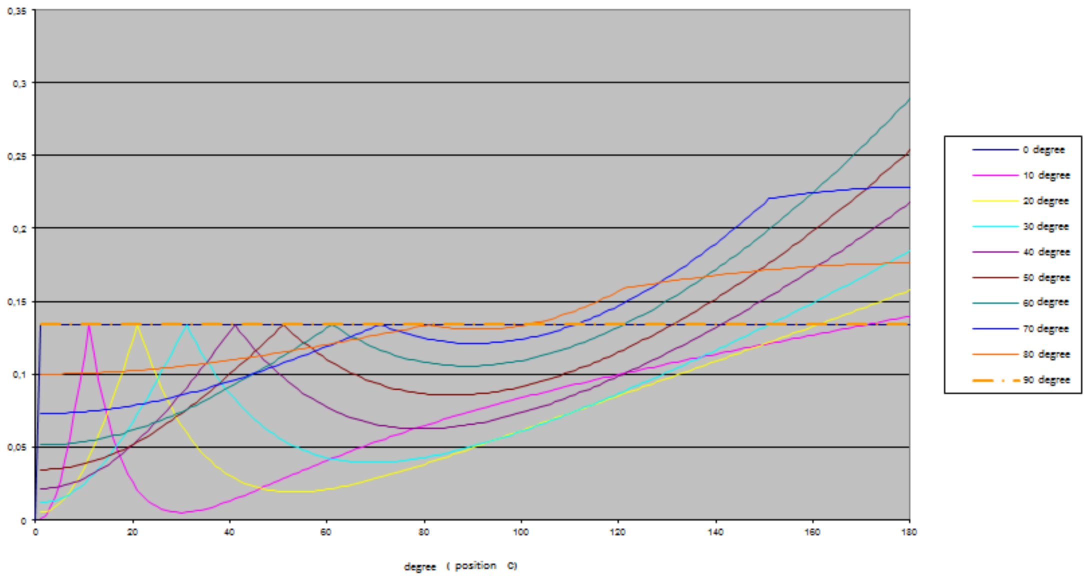


Fig. 2. Form factors of triangles of different shapes.

Analysis of the behavior the form factor of the quadrangles

In this case, we are faced with a situation, where the number of degrees of freedom of a geometric figure can not be identified by a single value index η /4/. In particular, for a square and a diamond the value of the index is the same. We are able to distinguish between them by using a value for the form factor of order 3 quasicontour. For quasicontour contours that form a rectangle the form factor always coincides with the form factor of a right triangle. Fig. 3 shows the dependence of the shape of rectangular quadrangle. The ratio α from lesser to greater is selected as the independent variable.

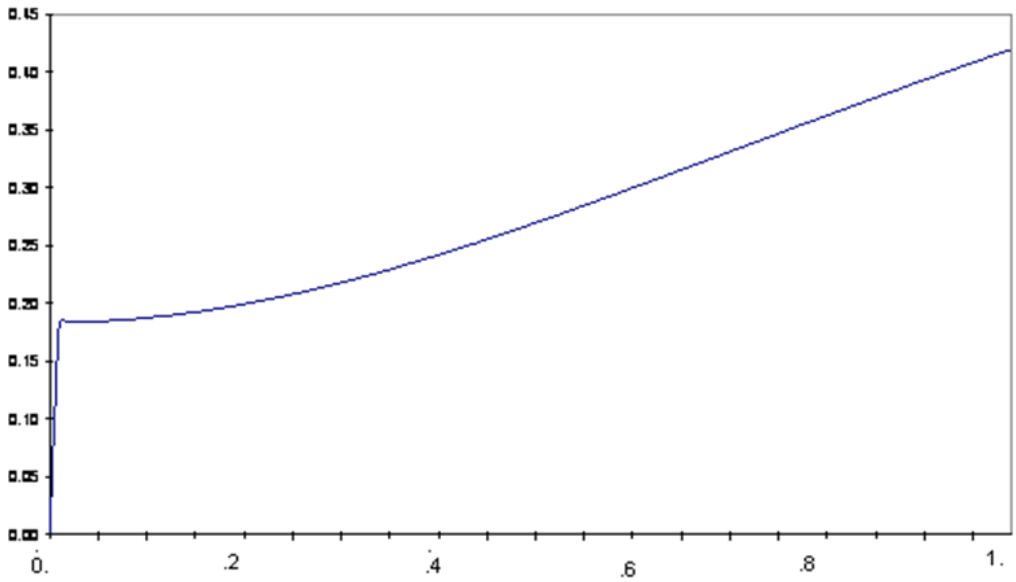


Fig. 3. The dependence of the form factor of the relationship of the parties for rectangles.

From the figure above, it follows that the value of the form factor, which is a monotonically increasing function of α, changes in the range 0.19-0.423, with a singular point α = 0 with a value of 0.

Form factors of regular polygons

Regular polygons should be used to determine the minimum requirements for the digitization of the images, in which it makes sense to solve the problem of the select shape using the contour of the corresponding order. Therefore, we give the corresponding diagram of the form factor values, calculated according to the formula $\gamma(n) = 1 - 1/\sqrt{n-1};\, n = 3, 4, 5\cdots$

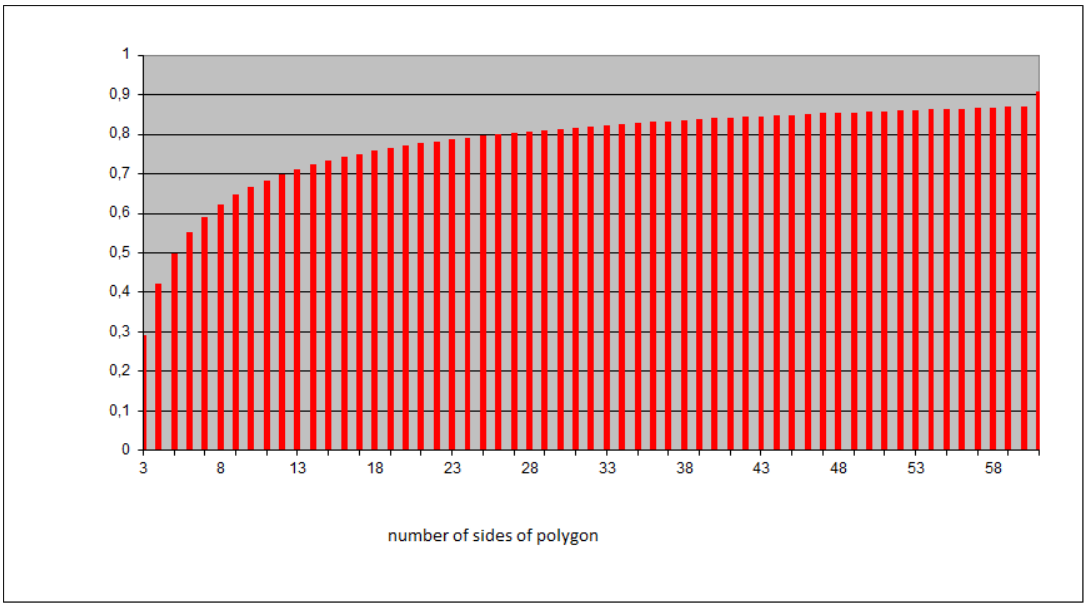


Fig. 4. Form factors of regular polygons

Effect of sampling on the possibility of determining the form shapes.

We proceed to define the required (minimum) parameters of the digital image, for which it is possible, by the methods of contour analysis, to distinguish the regular polygons that form simple contours of the corresponding order on the background of the circle.

The process of analyzing a complex image is, in particular, fragmentation into separate sections. On a pre-allocated site one should decide what the simplest figuresfor the image. We assume the selected area is a square, the size of which is determined by the number of pixels, m. In considering the impact of digitizing images in allocating figures, the simplest form of the method of contour analysis of the pixel size should be regarded as a basic parameter. The objective of the survey was to determine the minimum size of the contour (i. e., number of pixels), which can guarantee to select a regular polygon contour. The boundary figure for the growth of the numbers of sides of a polygon is a circle. A digital image of a circle is a standard in the problem of the differences of the polygon from the circle, by using the methods of contour analysis.

The orders of the contours of polygons and circles, n_1 and n_2 , within the chosen drawing is usually different. Their respective values and the values of the form factors will be considered as two characteristics that should be used when deciding. Choosing as the reference values, n_2 and $\gamma(n_2)$, for the circle, we introduce the following thresholds, allowing the estimates from references:

for orders contours Δ = 2;

for the form factors $\varepsilon_i = 0.02\gamma(n_i); i = 1, 2.$

Then, when we select the range of *m, the* solution of the difference image of the polygon from the circumference is taken with an equity of one of the two inequalities

$$|n_i - n_i'| > 2 \text{ or } |\gamma(n_i) - \gamma(n')\ | > \varepsilon_i; i = 1, 2.$$

Where the prime is the labeled parameter estimates of the current image.

In view of the image the captured figures of regular polygons are distorted, when you turn them by any angle on the plane with respect to the chosen (vertical) direction by. In the paper the influence of the orientation of the polygons, with the number of faces from 3 to 6, was carried out to determine the minimum size of *m*, ensuring the selection of their shape on the selected image area. The orientation of the polygons varied in the range of angles equal π/*n* (*n* namber of edges).

Studies was conducted for the compositions of algorithms:

- • allocation of polygons by the initial formed contour of the image (simple algorithm)
- • contour subjected to compression pointwise
- • compression contour was carried out by a linear approximation of its structure
- • the created contours, using the above treatment options, were equalized by the following criteria:
  - • a reduction of the order of the circuit was carried out on a minimum area of the excluded section
  - • in addition to the basic criterion, when an ambiguous situation arises (equality of the minimum area of several units), selection was carried out by

the minimum level of the final vector, which is the sum of the vectors of equal units.

The main results obtained using the contour image processing without equalization are presented in the table, which shows the initial diameter of the circle described around a polygon, with which it is possible to hold their automatic selection using the proposed criteria

Table. Values of the minimum diameters

The order of the contour / algorithm	Simple	Pointwise contraction	Linear contraction
Third	8	8	8
Fourth	16	10	10
Fifth	12	10	10
Sixth	16	11	11

Analysis of the results shows that the practical solution to highlight structural elements by contour analysis can be done, if we restrict the following composition of figures in the plane, the order of which does not exceed six, and to figures of the second order. For this composition in Figure 5 the corresponding estimates of the order and the form factor for polygons and circles, with an image size corresponding to the table and reduced by one is shown. Numbers in the legend in the figures represent the true order of the regular polygons, while the image of a circle appears as round.

The presented parameters, together with the size of the selected item, can be used as references in the allocation of the structural elements in the original image. The main drawback here is the essential difference between the order of the contour used and the true value of the order of the released figures.

This disadvantage is eliminated by equalization contours algorithms, built at the beginning of the outline analysis. Studies were conducted using six versions of the algorithm as shown in Figure 6-7, as the dependence of the range of variation of the shape at different angles of orientation of the original image size. The numbers in the legend indicate the structure of the processing algorithm:

- 0 – equalization simple contour by using 1-st test
- 1 – equalization simple contour by using 2-nd test
- 2 – equalization pointwise contraction contour by using 1-st test
- 3 – equalization pointwise contraction contour by using 2-nd test
- 4 – equalization linear contraction contour by using 1-st test
- 5 – equalization linear contraction contour by using 2-nd test

Yellow in the figures shows the average values of the form factors, and a solid black line corresponds to the theoretical value of the form factor of the contour polygon of the corresponding order.

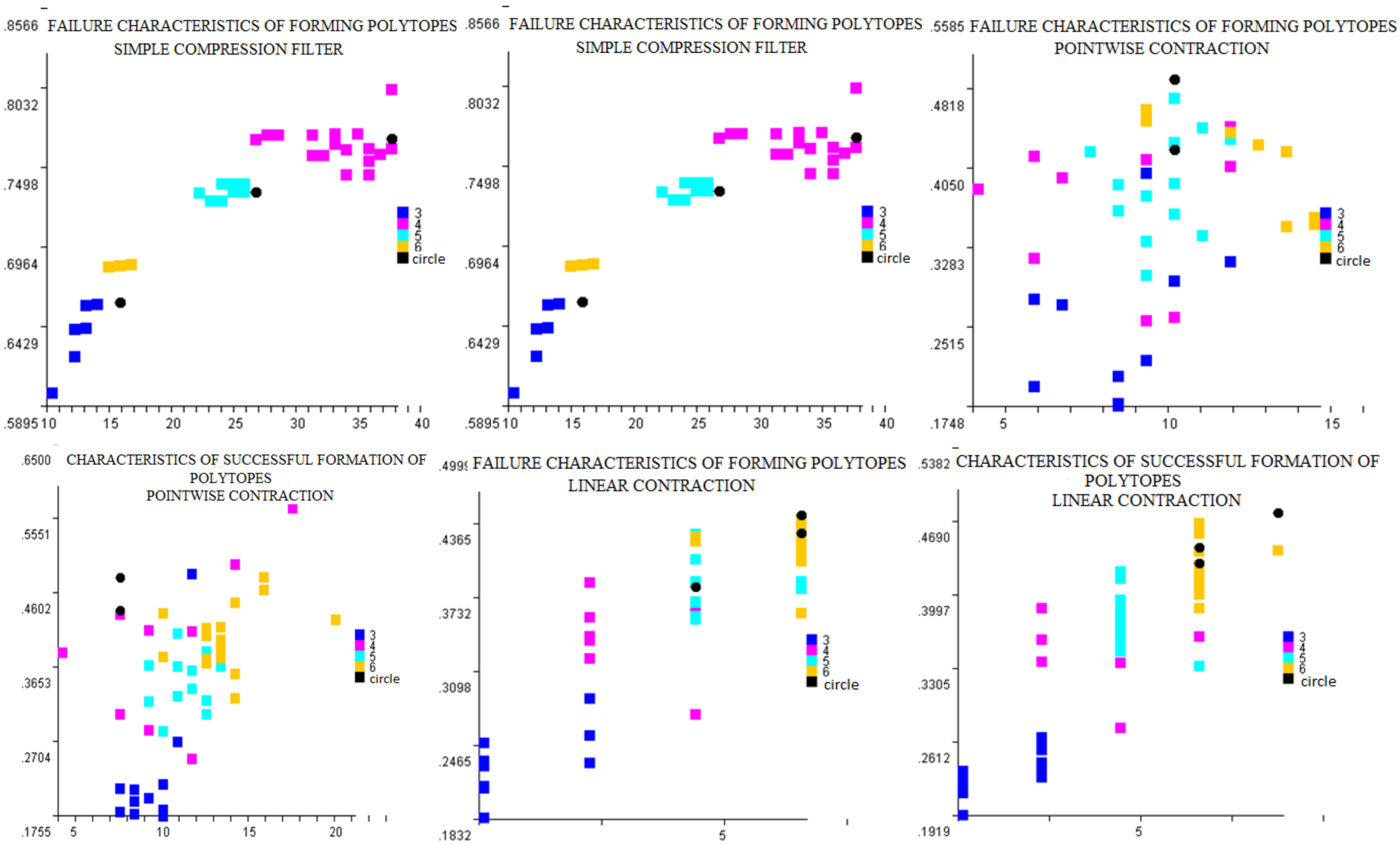
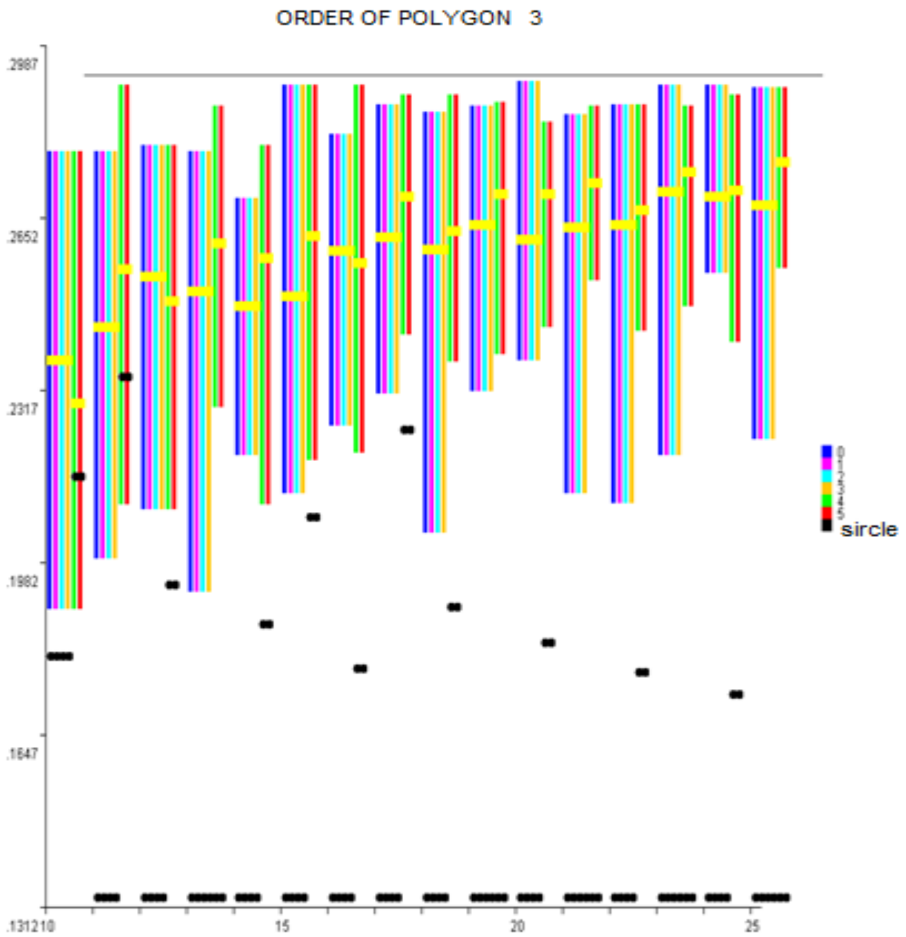


Fig. 5. Possible allocation of the structural element space objects by simple algorithms



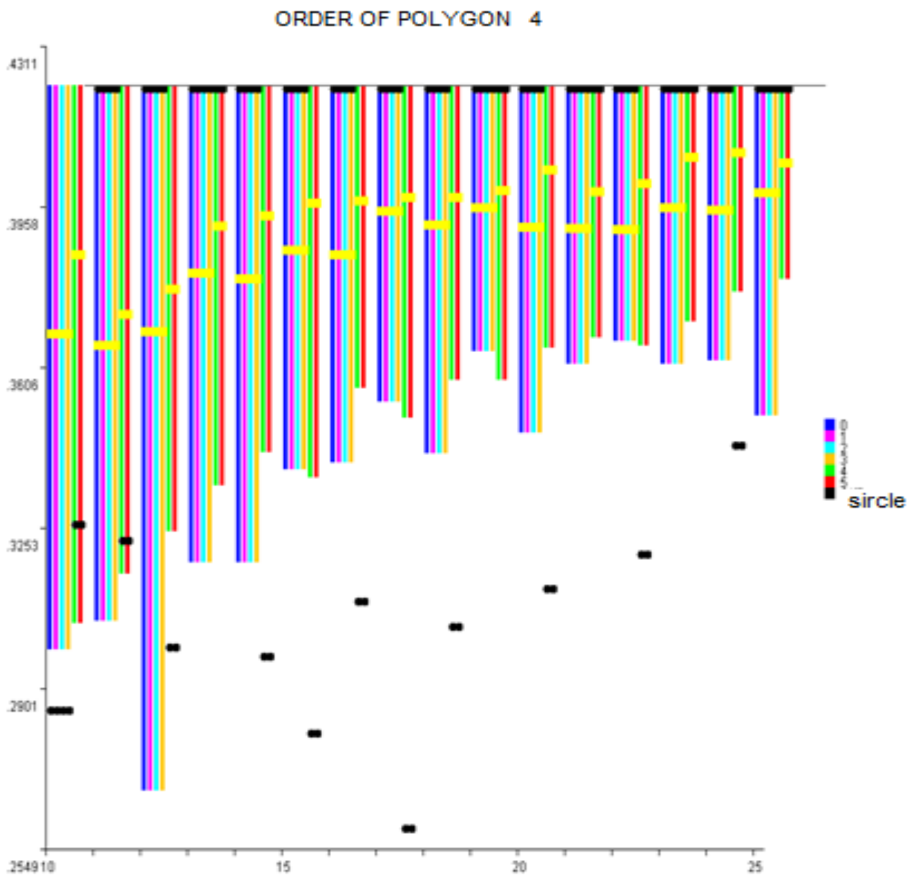


Fig. 6. Recognition with equalization

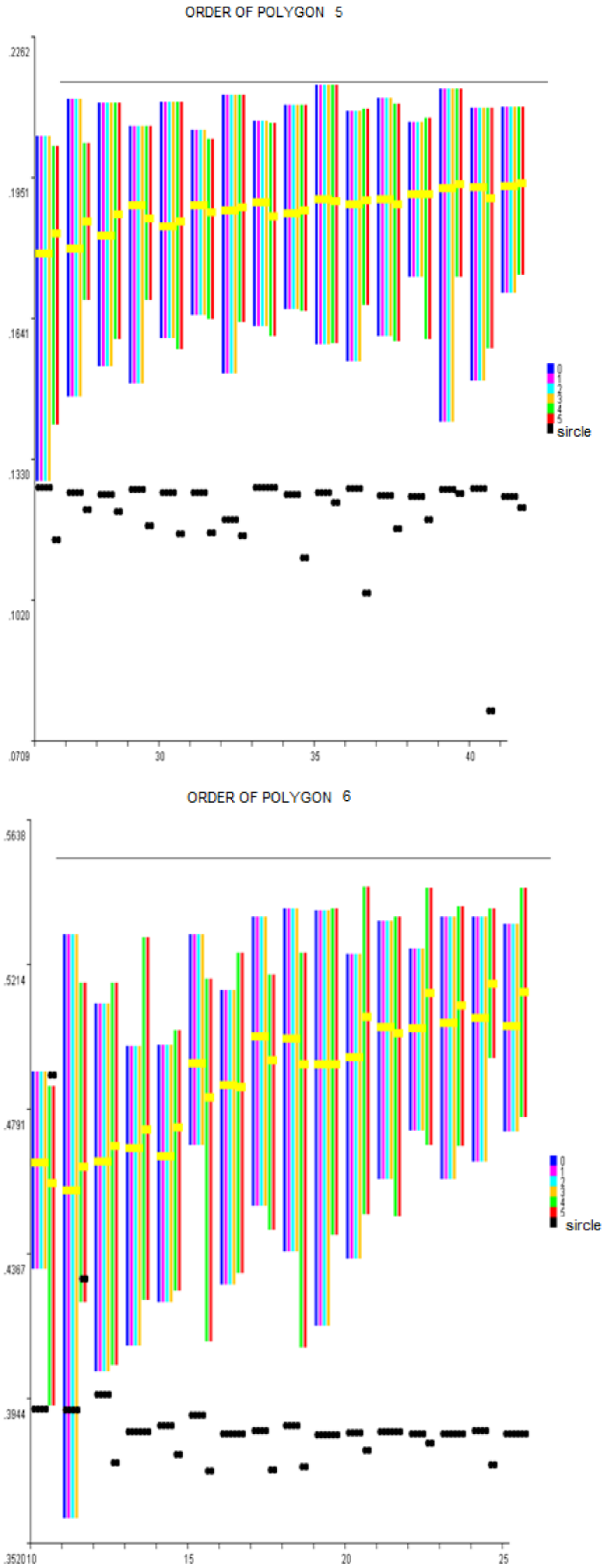


Fig. 7. Recognition with equalization

The analysis of the results allowed us to draw the following conclusions.

Using the pointwise compression and sophisticated quality criteria in equalization algorithms does not significantly change the results of treatment and, therefore, is inappropriate.

Equalization for contour extraction of the third order is expedient to carry out, using the algorithm number 0

Equalization for contour extraction of the fourth order is expedient to carry out, using the algorithm number 5

Contour of a higher order may hold any algorithm.

Algorithm for image alignment

Estimates of the parameters of the image position on the frame and its scale is needed to match consecutive images when required with a combination of frames, to assess the change in the position with respect to the reference point images. They turn with respect to each other and there is a possible scope of extension.

We have developed an appropriate method for estimating the above parameters with the use of the contour analysis, and then combine the different images. The following figures are examples that characterize the quality of the solution of a composite image using the proposed algorithm.

The following figure shows the results of combining the two images, the initial orientation of the contour, which is shown in the left figure, and the result of overlapping contours on the right. The combining algorithm includes equalization of the initial contour to the contour of the selected order (in the example the 20-th order). The allocation sections the maximum lengths of the contours, their turns, extensions, and possible reflections. In this process of transformation, estimates of the transformation parameters of individual frames are constructed, and the information is transferred to the final frame.

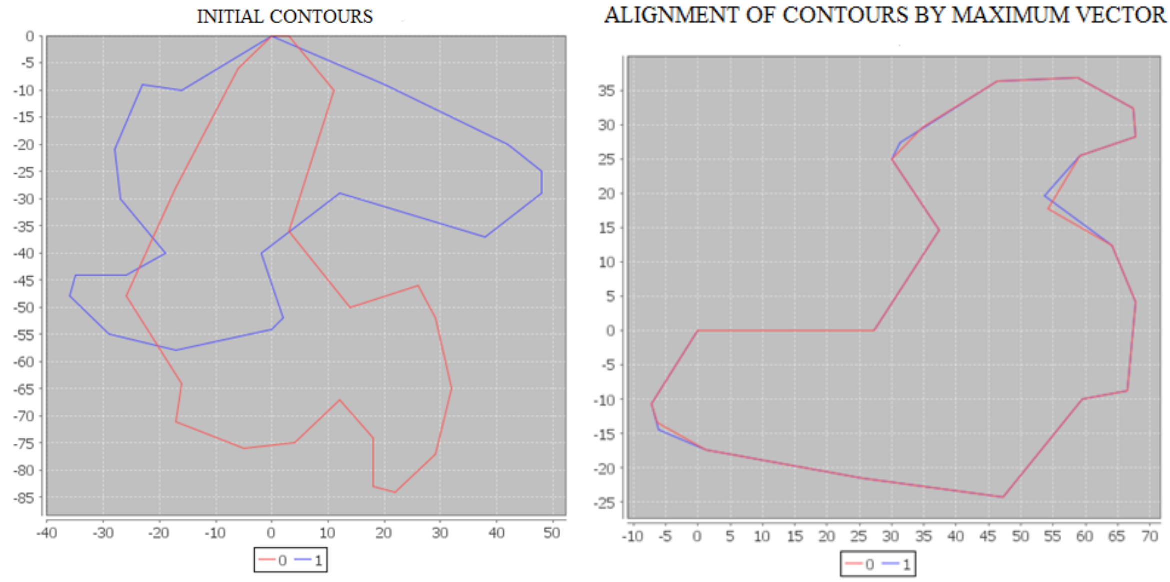


Fig. 8. Result of alignment contours of two images from serial frames.

The result of the transformation is shown in Figure 9, as the difference between the intensities of the two images combined on each cell.

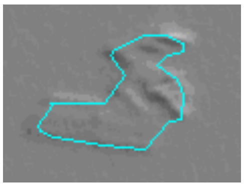


Fig. 9. Result of alignment of two images from different frames.

The figure shows the position of contour found in blue, zero (exact match of intensities of the two images on the cells) - gray (pixel intensity is 127). The pixel intensity, the level which is different from zero, varys with the magnitude and sign of the difference formed. Analysis of the results showed the possible emergence of a significant discrepancy. One of the reasons for the phenomenon, can be the digitized source images.

The above image combination procedure was supplemented by an algorithm for local variation of the image positions relative to each other, in a range of some cells in order to refine the combination. A criterion of minimum module residual intensity, normalized to the number of significant pixels, was selected as a criterion for matching images. The results are shown in the following figures.

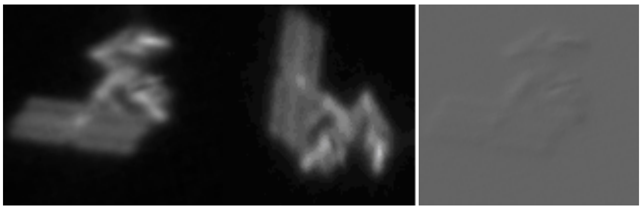


Fig. 10 original images and the difference frame obtained after proposed conversion.

The original image and the difference ISS frame formed by using the results of image registration is shown in fig. 10. The parameters of this frame are determined using the developed algorithm. The following figure shows a two-dimensional and three-dimensional representation of the residuals of the intensities in the image cells, the mean value of the modulus of discrepancy ≈ 3.5 units. This result confirms the efficiency of the proposed method.

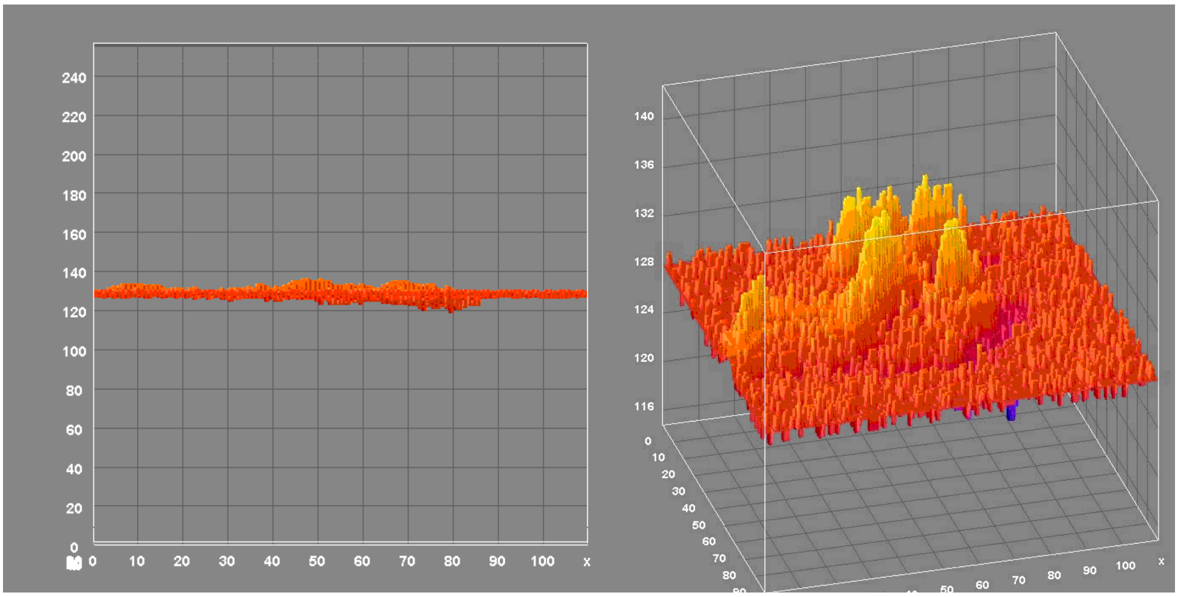


Рис. 11 Распределения относительных отклонений интенсивностей на совмещённом кадре.

Main results

- A model, describing the contour of the object as an approximation to the structure of a closed polygon of the corresponding order, was proposed. To solve this problem synthesized compression algorithms and equalization outlines were given.
- The algorithms of the pointwise and linear compression and equalization algorithms, with a minimum area criterion for the removal from the contour of the current section, and an additional criterion for disambiguation, using a minimum length of the vector in the reduced section, are developed .
- A quantitative scalar form factor was introduced. This is invariant to transformations of scaling and rotation of the contour in the plane, the shift of its initial position, and the displacement of the image on the frame.
- In order to determine the potential allocation of structural elements in the images of the objects by the contour analysis methods, a numerical study of parameters of regular polygon shapes up to 6th order and second-order figures was carried out.
- A part of the figures is chosen, the use of which should be appropriate in the problem of solving for the separate typical structures in the original images of space objects.
- The investigation of the quality of the six variants of the algorithms in the analysis of the structure of the contour design elements, with the influence of the digitization of real images and the orientation of edges in the picture, is carried out.
- The reference description of contours, the use of which is reasonable in the allocation of appropriate structural elements, is formed.
- Ranking equalization algorithms, regarding priorities in the allocation of their use in the selection contours of the corresponding orders, is realized.
- An algorithm for matching images of the object obtained on different frames, using the distinguished contours of objects, was proposed

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