Встановлено, що відомі методи сегментування зображень не можуть бути напряму застосовані до сегментування оптико-електронних зображень бортових систем дистанційного зондування Землі. Сформульовано математична задача сегментування таких зображень. Встановлено, що результатом сегментування зображень бортових систем дистанційного зондування Землі є розділення зображення на штучні об'єкти (об'єкти інтересу) та природні об'єкти (фон). Запропоновано для сегментування зображень використання методу штучної бджолиної колонії. Викладена сутність методу, який передбачає визначення положень агентів, їх міграцію, умов зупинки ітераційного процесу за критерієм мінімуму цільової функції та визначення оптимального значення порогового рівня. Введена цільова функція, що має фізичний смисл суми дисперсії яскравості сегментів сегментованого зображення. Сформульовано оптимізаційна задача сегментування зображення бортової системи оптико-електронного спостереження, яка полягає в мінімізації цільової функції при певних припущеннях та обмеженнях.

Наведені результати експериментального дослідження застосування методу штучної бджолиної колонії до сегментування оптико-електронного зображення. Експериментальні дослідження сегментування оптико-електронного зображення підтвердили працездатність методу штучної бджолиної колонії. На сегментованому зображенні для прикладу визначені можливі об'єкти інтересу, а саме: ємності з нафтою або паливом для літаків, літаки, аеродромні споруди тощо.

Проведена візуальна оцінка якості сегментування. Розраховані помилки першого та другого роду. Встановлено, що застосування методу штучної бджолиної колонії дозволить підвищити якість обробки оптико-електронних зображень. При цьому помилки сегментування першого та другого роду знижені в середньому на величину від 7 % до 33 %.

Ключові слова: дистанційне зондування Землі, зображення, сегментування, метод штучної бджолиної колонії

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SEGMENTATION OF OPTICAL-ELECTRONIC IMAGES FROM ON-BOARD SYSTEMS OF REMOTE SENSING OF THE EARTH BY THE ARTIFICIAL BEE COLONY METHOD

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1. Introduction

It is known that obtaining materials on remote sensing of the Earth from space and air makes it possible to solve a large number of complicated and important tasks in various areas of life [1]. Such tasks include, for example, environmental issues and issues related to environmental monitoring, nature management and effective land management, military affairs, control of terrorism, mapping, etc. [1]. The result of the processing of materials on remote sensing of the Earth depends on their segmentation [2–3]. The following factors stipulate expediency of development of an effective method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth [3]:

– improvement of the special hardware and software for automation of the most complicated stages of processing of information on observation;

– a decrease in processing time and an increase in reliability of resulting documents;

– intellectualization of data processing processes (detailed observation of objects of interest, solution of large-scale thematic tasks for large territories).

2. Literature review and problem statement

The body of research into the development, modernization and application of methods of segmentation of optical-electronic images is constantly increasing [3–9], because of the significant impact of segmentation on the final processing quality and decoding of an image. Let us conduct an analysis of known segmented methods also used to segment images of on-board systems for remote sensing of the Earth.

Paper [4] proposes the k-means method for segmentation of images. The main disadvantages of the method are:

– results depend largely on initial parameters of the method and specificity of an image;

– a segmentation result is achieved as a result of multiple iterations.

The specified disadvantages complicate image processing in the real time scale.

Work [5] proposes the Otsu segmentation method. The main disadvantage of the method is sensitivity of threshold binarization to unevenness of brightness of an image due to the fact that there is only one global threshold introduced.

Paper [6] proposes highlighting of contours of objects of interest by methods of spatial differentiation, including the methods of Sobel, Prewitt, Kirsch, Wallis and Canny for segmentation of an image. The main disadvantages of the mentioned methods are the presence of gaps, points and strokes, which create a background noise, necessity to know the initial approximation to a desired boundary and high calculation costs.

Authors of papers [7–9] use evolutionary methods for segmentation of medical images. It is not possible to use well-known evolutionary methods of segmentation of medical images [7–9] to segment images of remote sensing of the Earth. Firstly, because of different conditions for formation of images and because of an informational component presented in an image. Secondly, because processing of images solves different tasks.

The main disadvantage of neural network methods [10] of segmentation of images is a need for operator involvement and a need for pre-processing of images. Different initial conditions for obtaining of images lead to different end results of segmentation. Training of a neural network occurs based on random selection, final weight coefficients for source neurons depend on the initial sequence. Completion of a training process has no base with strict optimization mathematical models. Thus, neural network methods are not suitable for segmentation of images of on-board systems of remote sensing of the Earth.

Authors of [11–13] developed non-parametric methods of clustering and methods of spectral-texture segmentation of satellite images of high spatial resolution, which are effective in terms of performance of calculation procedures. But it is possible to apply the methods [11–13] for segmentation of large landscapes (a forest, a field, water surface, etc.) only on images of on-board systems of remote sensing of the Earth.

Authors of works [14–15] developed methods of segmentation of objects of the earth's surface by the data of hyperspectral observation with the use of methods of artificial intelligence, namely, clustering based on fuzzy sets, artificial neural networks and genetic methods. The novelty of the methods [14–15] is hybridization of known methods of artificial intelligence and their application for segmentation of an image obtained as a result of hyperspectral observation. The main disadvantage of these methods is a need to train artificial neural networks, which reduces effectiveness of the proposed segmentation methods greatly. In addition, there are some difficulties in determination of the function of the normalized mutual information and the average normalized mutual information.

Specialized software is necessary in the technology of computer decoding of data on remote sensing of the Earth. The most commonly used specialized software for remote sensing data processing are: ERDAS IMAGINE, TNTmips, ER Mapper, ENVI, GRASS, INTERGRAPH, Arc View, ScanViewer, IMAGE Transformer, MODIS Processor, IRS Processor, ScanMagic, SCANEX NERIS, LESSA and others [16–20]. An analysis of operation of this specialized software showed that some of them do not solve segmentation task at all, while others use known segmentation techniques analyzed above.

Authors of [3, 21] propose to segment images of on-board systems of observation using the ant colony optimization (ACO) method. The main disadvantage of the ACO method is re-segmentation – presence of a large number of contours of small-sized objects («trash» objects) on a segmented image.

Paper [22] proposes to segment images of on-board systems of observation using swarm methods. However, there is only a reference to a need to use a fitness function in an optimization problem in paper [22]. But there are no justification of the form and determination of a physical nature of components of a fitness function.

Thus, one cannot apply the existing image segmentation methods directly to segmentation of images of on-board systems of remote sensing of the Earth. Firstly, they do not take into consideration peculiarities of imaging of on-board systems of remote sensing of the Earth. Secondly, they do not take into consideration complexity of images of remote sensing of the Earth, namely:

– presence of a large number of heterogeneous objects;

– objects in an image belong to different structural-spatial elements;

– each type of object has its own significant characteristics; it is necessary to take them into consideration;

– objects are morphologically complex structures;

– objects are compact and low-contrast with a background.

Consequently, the task of the development of a segmentation method, which is free from the main disadvantages of the known methods, is expedient for segmentation of images of on-board systems of remote sensing of the Earth. Let us select the method of artificial bee colony [23–28] for further research on segmentation of optical-electronic images of on-board systems of remote sensing of the Earth. Authors of known works [23–28] applied the method of artificial bee colony to find global optimums of complex functions (spherical function, Rastrigin function, Schwefel function, and others). The main advantages of the method are:

– disinclination to looping in local optima;

– multi-agency in implementation;

– ability to adapt to environmental changes;

– possibility of application for solution of both discrete and continuous optimization tasks;

– search for a better solution based on decisions of all agents (bees).

3. The aim and objectives of the study

The objective of the study is to improve segmentation of optical-electronic images of on-board systems of remote sensing of the Earth using the artificial bee colony method.

To achieve the set aim, the following tasks have been solved:

– development of a method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth;

– substantiation of a choice of a fitness function for segmentation of an optical-electronic image;

– carrying out an experimental research on segmentation using the developed method of a typical optical-electronic image of the on-board system of remote sensing of the Earth;

– evaluation of the segmentation quality of a typical optical-electronic image of the on-board system of remote sensing of the Earth by the developed method and the known segmentation methods.

4. Materials to study the segmentation of optical-electronic images of on-board systems of remote sensing of the Earth using the artificial bee colony method

4. 1. Development of the method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth

We determine segmentation of the original optical-electronic image $f(x, y)$ from the following expression (1):

$$f(x,y) \to fs(x,y), \quad (1)$$

where $f(x, y)$ is the original optical-electronic image; $fs(x, y)$ is the segmented image.

Segmentation involves displaying of pixels (points) of an original image with (x, y) coordinates in some space of signs and introduction of a metric (measure of proximity) in this space of signs. We use brightness of pixels of an image and its properties, namely discontinuity and homogeneity in some color space, as a sign. The metric is a distance between brightness of pixels in a color space. According to (1), segmentation of an original image involves division of $f(x, y)$ into B_i segments satisfying the conditions (2):

$$\begin{cases} \bigcup\limits_{i=1}^{K} B_i = B; \\ B_i \cap B_j = \varnothing, \text{ for } i \neq j; \ \forall i,j = \overline{1,K}; \\ LP(B_i) = 1; \ \forall i = \overline{1,K}; \\ LP(B_i \cap B_j) = 0, \text{ for } i \neq j; \ \forall i,j = \overline{1,K}, \end{cases} \quad (2)$$

where B: $B=\{B_1, B_2,..., B_K\}$ are the segments in $fs(x, y)$ image; K is the number of B_i, $(i=1, 2,..., K)$; LP is the predicate defined on B and it takes «1» value – the truth when any pair of points from each B_i segment satisfies a certain homogeneity criterion – expression (3):

$$LP(B_i) = \begin{cases} 1, & \text{for } f(x_1, y_1) = ... = f(x_M, y_M); \\ 0, & \text{others}, \end{cases} \quad (3)$$

where $(x_m, y_m) \in B_i$; $m=1, 2,..., M$; M is the number of points in B_i segment.

The result of segmentation of images of on-board systems of remote sensing of the Earth is the division of an image into artificial objects (objects of interest) and natural objects (a background). That is, a number of segments in a segmented image is equal to $K=2$.

It is necessary to determine the optimal segmentation threshold to segment an optical-electronic image and to divide it into artificial and natural objects. We use the method of artificial bee colony to determine this segmentation threshold.

We present the method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth in the following form. Fig. 1 shows the positions of agents of the method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth.

1. Initialization of the initial positions of agents in the image (Fig. 1, *a*). The condition is correct only for n^s spy agents on the first iteration ($j=1$) (expression (4)):

$$\mathbf{X}_{i1} = \text{rand}(f(\mathbf{X})), \quad (4)$$

where $\mathbf{X}=(x, y)$ is the vector of positions of agents; $\mathbf{X}_{i1}= (x_{i1}, y_{i1})$ is the vector of positions of agents on the first iteration; rand$(f(\mathbf{X}))$ is the generator of random numbers; $i=1,..., n^s$; n^s is the number of spy agents on the first iteration.

2. Determination of $\varphi(\mathbf{X}_{ij})$ fitness function of each i-th ($i=1, 2,..., |S|$; $|S|$ – a number of agents) in the current j-th iteration.

3. Formation of the best N_{ij}^b and perspective N_{ij}^g positions of agents taking into consideration values of $\varphi(\mathbf{X}_{ij})$ fitness function for each i-th agent.

4. Migration of agents (Fig. 1, *b*). Working agents head to suburbs of best and perspective positions after formation of the best and perspective positions of agents. c^b of working agents head to suburbs of each better position, c^g of working agents head to suburbs of each promising position. We determine positions of all working agents by the expressions (5), (6):

$$\mathbf{X}_{((i-1)c^b+k)j} = N_{i(j-1)}^b + \text{Rnd} \cdot \text{rad}, \quad (5)$$

where $\mathbf{X}_{((i-1)c^b+k)j}$ is the vector of positions of the best agents on j-th iteration; N_{ij}^b is the best position of i-th agent on j-th iteration; $i=1,..., n^b$, $k=1,..., c^b$; n^b is the number of best positions on j-th iteration; c^b is the number of agents, which head (migrate) to the best positions; Rnd is the random number; rad is the coefficient, which determines the variance of agents when they go to the best and promising positions;

$$\mathbf{X}_{(n^b c^b+(i-1)c^b+k)j} = N_{i(j-1)}^g + \text{Rnd} \cdot \text{rad}, \quad (6)$$

where N_{ij}^g is the promising position of i-th agent on j-th iteration; $i=1,..., n^g$, $k=1,..., c^g$, n^g is the number of perspective positions on j-th iteration; c^g is the number of agents, which head (migrate) to promising positions.

Spy agents head to positions with random coordinates distributed evenly throughout the permissible range of values (throughout an image) (7):

$$\mathbf{X}_{(n^b c^b + n^g c^g + i)\,j} = \mathrm{rand}(f(\mathbf{X})), \tag{7}$$

where $i=1,...,n^s$, n^s is the number of spy agents on j-th iteration.

5. The coefficients (parameters) of the method used in expressions (5)–(6) belong to the vector of the initial parameters of the coefficients of the method $\mathbf{P}=\{n^s, n^b, n^g, c^b, c^g, \mathrm{rad}, rx, ry\}$ (rx and ry are the sizes of suburbs of the best and perspective positions by the corresponding coordinates).

6. The initial data of the method is determination of the optimal position of agents (Fig. 1, *c*), which provides the minimum or maximum value of $\varphi(\mathbf{X}_{ij})$ fitness function and the optimal value of th segmentation threshold.

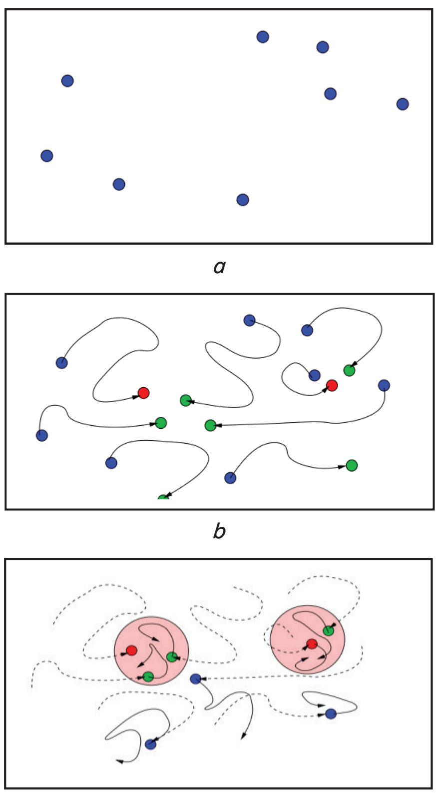


Fig. 1. The positions of agents of the method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth: *a* – initialization of the initial positions; *b* – migration; *c* – determination of the optimal position

Thus, Fig. 2 shows a generalized scheme of the method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth based on the method of artificial bee colony.

The base of the behavior of agents of the artificial bee colony method is self-organization. Self-organization is a set of dynamic mechanisms, which regulate the system globally through interaction of components at a lower level without direct interaction between these components. The main components of the self-organization of agents of the artificial bee colony method at segmentation of optical-electronic images of on-board systems of remote sensing of the Earth are as follows:

– positive feedback achieved through implementation of simple behavioral empirical techniques, which provide finding of solutions. The positive feedback manifests itself when agents begin to move to the specified source of resources based on information from other agents;

– negative feedback balances positive feedback, which leads to stabilization of collective behavior. The negative feedback manifests itself when agents decide that the found position is worse based on information from other agents;

– instability of positive feedback: the base of the behavior of agents is stochastic rules, so random deviations in decisions are the basis for finding of new solutions. A missed agent can find new unworked positions and lead other agents;

– requirement of multiple interactions between agents, which provides achievement of new best solutions. The multiplicity of interaction of the method of artificial bee colony consists in the fact that information about the position found by one agent is available for all other agents.

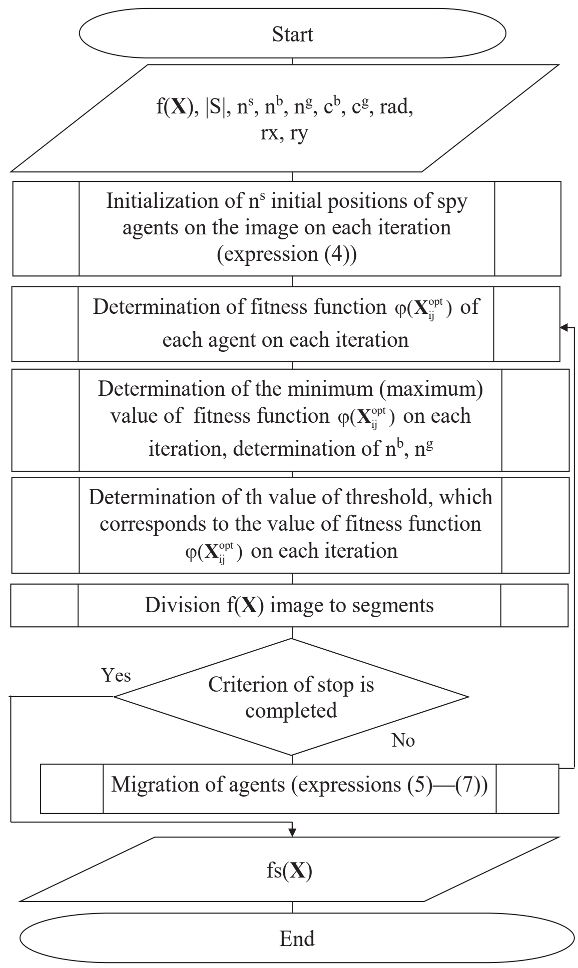


Fig. 2. The generalized scheme of the method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth

It is necessary to determine $\varphi(\mathbf{X}_{ij})$ fitness function and formulate an optimization problem for determination of the optimal value of the segmentation threshold to apply the method (Fig. 2) to segmentation of optical-electronic images of on-board systems of remote sensing of the Earth.

There are the following requirements to $\varphi(\mathbf{X}_{ij})$ fitness function: satisfaction of the condition of the adequacy of the task; application of the minimum of calculation resource; minimum of a number of local optima; it should not be too «sharp».

4. 2. Substantiation of the choice of the fitness function for segmentation of an optical-electronic image of the on-board system of remote sensing of the Earth

Let us consider model images (Fig. 3) to substantiate the choice of the fitness function of the method of segmentation of an optical-electronic image of the on-board system of remote sensing of the Earth. Fig. 3, *a* shows the case when the object (inner square) and the background are separated. Fig. 3, *b* shows the case when the object (inner square) and the background are not separatedThe background size is much larger than the size of the object. The brightness of pixels of the object and the background is distributed according to the normal law with the following parameters (Fig. 4):

– mathematical expectation: $\mu_1=0.75$ for the object; $\mu_2=0.25$ for the background;

– root-mean-square deviation: $\sigma_1=\sigma_2=0.01$ for the object and the background (the object and the background are separated), $\sigma_1=\sigma_2=0.1$ (the object and the background are not separated).

Segmentation of a model image means determination of *th* optimal threshold value of the object's separation from the background. Let us assume that we found the threshold. Then, for the case when the object and background are separated (Fig. 3, *a*), we binarize the image and consider the dependence of the value of variance of intensity of under threshold $D_1(th)$ and above threshold $D_2(th)$ pixels as a function of *th* threshold. For the boundary values of the threshold $D_1(th=0)=0$, $D_2(th=0)=D_0$, $D_1(th=1)=D_0$, $D_2(th=1)=0$, where D_0 is the variance of the model image (Fig. 3, *a*).

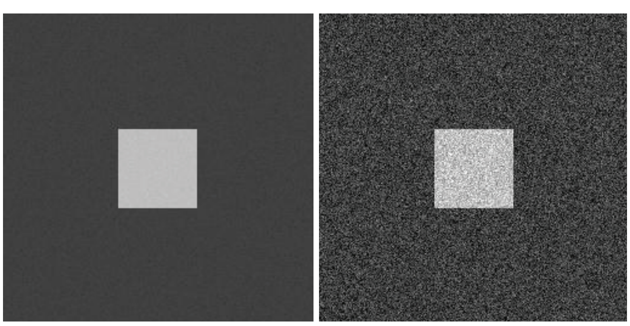
To determine the expression for D_0 variance of the model image, we perform calculations for the mathematical expectation of the model image by expression (8):

$$\mu = \frac{\tilde{s}_1\mu_1^2 + \tilde{s}_2\mu_2^2}{\tilde{s}_1 + \tilde{s}_2}, \qquad (8)$$

where $\tilde{s}_1$, $\tilde{s}_2$ are the areas (number of pixels) of the object and the background, respectively, in the model image (Fig. 3, *a*).

One can easily determine the value of D_0 by expression (9):

$$D_0 = \frac{\tilde{s}_1\mu_1^2 + \tilde{s}_2\mu_2^2}{\tilde{s}_1 + \tilde{s}_2} - \mu_1^2. \qquad (9)$$



a *b*

Fig. 3. The model images of the object and the background: *a* — the object and the background are separated; *b* — the object and the background are not separated

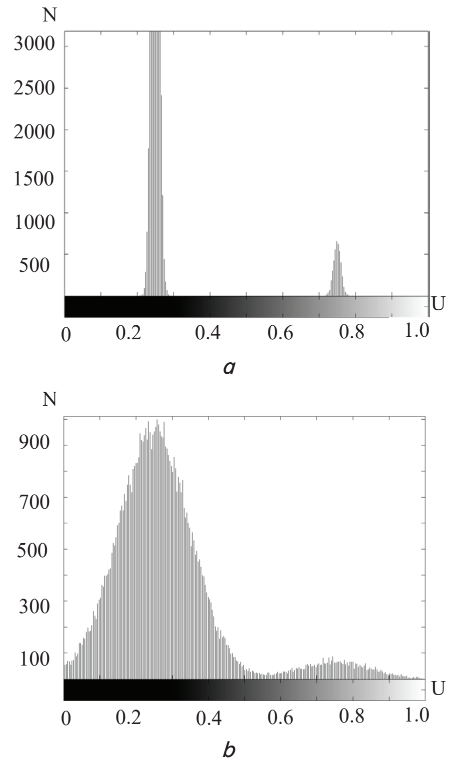


Fig. 4. The histograms of distribution of brightness of the model images: *a* — the object and the background are separated; *b* — the object and the background are not separated

If distributions of pixel intensity are not overlapped (Fig. 4, *a*), condition (10) must be satisfied:

$$(\mu_1 - 3\sigma_1) > (\mu_2 + 3\sigma_2). \qquad (10)$$

Then,

$$D_1((\mu_2 + 3\sigma_2) < th < (\mu_1 - 3\sigma_1)) = \sigma_2^2, \qquad (11)$$

$$D_2((\mu_2 + 3\sigma_2) < th < (\mu_1 - 3\sigma_1)) = \sigma_1^2. \qquad (12)$$

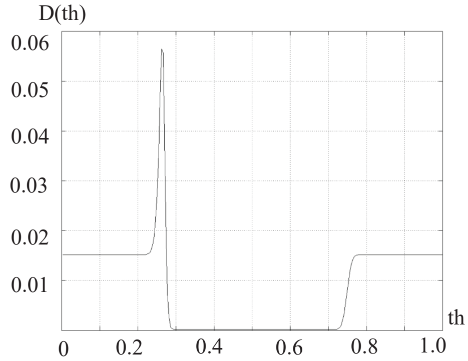
Let us consider $D(th)=D_1(th)+D_2(th)$ function. It has a physical meaning of the sum of variance of brightness of under threshold and above threshold pixels. We have:

$$D(th=0)=D(th=1)=D_0, \qquad (13)$$

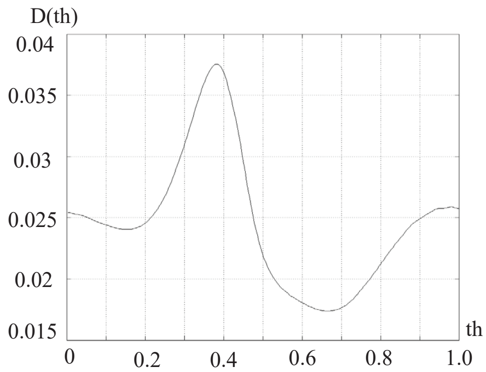
$$D((\mu_2 + 3\sigma_2) < th < (\mu_1 - 3\sigma_1)) = \sigma_1^2 + \sigma_2^2 < D_0. \qquad (14)$$

Thus, $D(th)$=min in the range of *th* threshold values, where the object is separated from the background.

Fig. 5 shows the form of $D(th)$ function for the model image of Fig. 3, *a*, when the object and the background are separated. In the case when the object and background are not separated (Fig. 3, *b*), the quantitative analysis is more complex and we do not give it in the study. But, nevertheless, the qualitative form of $D(th)$ function does not change. Fig. 5, *b* shows it. Thus, when using the artificial bee colony method for segmentation as an fitness function, it is expedient to choose $D(th)$ function – a sum of variance of brightness of segments of a segmented image.



a



b

Fig. 5. The form of $D(th)=D_1(th)+D_2(th)$ function: *a* — for the model image in Fig. 3, *a*; *b* — for the model image in Fig. 3, *b*

In general, expressions (15) to (20) represent the optimization problem of choosing of the threshold for segmentation of an optical-electronic image at each *j*-th iteration. It consists in minimization of the fitness function (15) at each *j*-th iteration, taking into consideration definitions and constraints (16) to (20).

$$D(th)=\sum_{j=1}^{K} D_j(th)\rightarrow \min; \quad (15)$$

$$D_j(th)=\frac{1}{N_{1j}(th)-1}\sum_{k=1}^{N_{1j}(th)}\left(U_{kj}-\mu_j(th)\right)^2 \text{ for } U_{kj}>th; \quad (16)$$

$$D_j(th)=\frac{1}{N_{0j}(th)-1}\sum_{k=1}^{N_{0j}(th)}\left(U_{kj}-\mu_j(th)\right)^2 \text{ for } U_{kj}\leq th; \quad (17)$$

$$\mu_j(th)=\frac{1}{N_{1j}(th)}\sum_{k=1}^{N_{1j}(th)} U_{kj} \text{ for } U_{kj}>th; \quad (18)$$

$$\mu_j(th)=\frac{1}{N_{0j}(th)}\sum_{k=1}^{N_{0j}(th)} U_{kj} \text{ for } U_{kj}\leq th; \quad (19)$$

$$0\leq th\leq U_{\max}, \quad (20)$$

where K is the number of segments; N_{0j} is the number of pixels in *j*-th segment, the brightness of which is less or equal to *th* threshold level; N_{1j} is the number of pixels in *j*-th segment, the brightness of which is greater than *th* threshold level; U_{kj} is the brightness of *k*-th pixel in *j*-th segment; μ_j is the mathematical expectation of brightness in *j*-th segment; $U_{\max}$ is the maximum value of the brightness of pixels in the image.

Iterative calculations solve the optimization problem. The condition for stopping of the method is the constancy of the value of the fitness function during 5 iterations.

4. 3. Results of an experimental study on application of the developed method of segmentation of a typical optical-electronic image from on-board system of remote sensing of the Earth

Let us consider application of the method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth based on the method of artificial bee colony. Fig. 6 shows the original optical-electronic image obtained from Ikonos spacecraft [22]. The image is in tone gradations of brightness of grey color from 0 to 255. The image size is (868×847) pixels. The original optical-electronic image (Fig. 6) is a complex structural typical image of on-board systems of remote sensing of the Earth and it contains:

– a large number of heterogeneous objects;

– objects in the image belong to different structural-spatial elements;

– each type of object has its own significant characteristics;

– objects are morphologically complex structures;

– objects are compact and small-contrast with the background.

Fig. 6. The original image [22]

Therefore, experimental research is limited to segmentation of only one typical image, which takes into consideration all peculiarities of complex structural optical-electronic images of on-board systems of remote sensing of the Earth.

Fig. 7 shows the results of segmentation of the original image (Fig. 6) by known methods (Otsu method, *k*-means method, Random forest method and ACO method).

Fig. 8 shows the result of segmentation of the original image (Fig. 6) developed by the method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth based on the method of artificial bee colony.

Comparison of the results of segmentation by the known methods (Fig. 7) and the developed method (Fig. 8) shows that visual definition of objects of interest are better in Fig. 8. An airplane, which escaped damage, and a damaged airplane, oil containers or fuel containers for airplanes, airfield facilities and others were identified as objects of interest.

Decryption of the mentioned objects of interest, recognition, thematic classification, etc. are subjects for further research and remain outside the scope of this study.

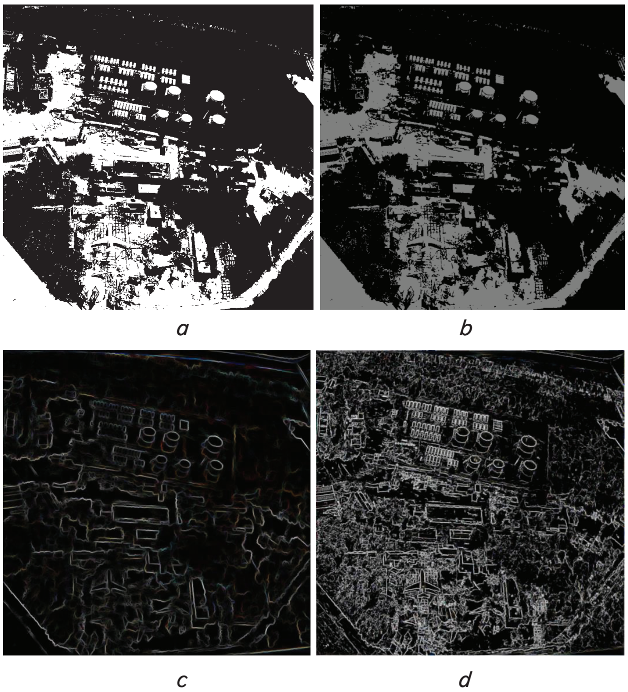


Fig. 7. The results of the segmentation of the original image by known methods: *a* – Otsu method; *b* – *k*-means method (k=2); *c* – Random forest method; *d* – ACO method

Fig. 8. The result of segmentation of the original image (Fig. 6) by the developed method

4. 4. Evaluation of the segmentation quality of a typical optical-electronic image of the on-board system of remote sensing of the Earth by the developed method and by known segmentation methods

Let us select segmentation errors of the first type and the second type as indicators for evaluation of the quality of segmentation of a typical optical-electronic image of the on-board system of remote sensing of the Earth by the developed method and the known segmentation methods. The criterion of maximum probability, which follows from the generalized criterion of the minimum of average risk [8–10], determines segmentation errors of the first (α_1) type and the second (β_2) type. Expressions (21), (22) determine errors in segmentation of the first type α_1 and the second type β_2, respectively [8–10]:

$$\alpha_1 = \frac{S_1(fs(\mathbf{X}))}{S_2(f(\mathbf{X}))}, \quad (21)$$

$$\beta_2 = 1 - \frac{S_3(fs(\mathbf{X}))}{S_4(f(\mathbf{X}))}, \quad (22)$$

where $S_1(fs(\mathbf{X}))$ is the area of the background segments, which is incorrectly attributed to objects of interest in the segmented image $fs(\mathbf{X})$; $S_2(f(\mathbf{X}))$ is the area of the background segments of the original image $f(\mathbf{X})$; $S_3(fs(\mathbf{X}))$ is the area of the correctly segmented objects of interest in the segmented image $fs(\mathbf{X})$; $S_4(f(\mathbf{X}))$ is the area of interest objects in the original image $f(\mathbf{X})$.

Table 1 shows the values of errors of the first type and the second type for different methods of segmentation calculated by expressions (21), (22). We selected Otsu method, Canny method, *k*-means (k=2, 3, 4) method, Random forest, and the ACO method as well-known methods.

Table 1

Evaluation of errors of the first type and the second type of segmentation of the optical-electronic image by different methods

The methods of segmentation	Otsu	Canny	*k*-means (k=2)	*k*-means (k=3)	*k*-means (k=4)	Random forest	ACO method	Developed method
α_1, %	18.30	10.50	18.50	17.30	15.50	15.90	4.15	3.70
β_2, %	25.70	14.30	25.80	23.70	20.30	17.76	6.84	6.35

Analysis of data from Table 1 shows improvement of the segmentation quality at application of the developed segmentation method based on the method of artificial bee colony. Segmentation errors of the first type and the second type decreased on average by the magnitude from 7 % to 33 %.

5. Discussion of results of segmentation of the optical-electronic image of the on-board system of remote sensing of the Earth using the method of artificial bee colony

We developed the method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth in this study. Formalized problem of segmentation of an optical-electronic image – expression (1). We established that the result of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth is division of an image into objects of interest and a background. It was proposed to apply the artificial bee colony method (4) to (6) to determine the segmentation threshold. The essence of the method of artificial bee colony consists in determination of initial positions of agents, their migration, determination of conditions for the stopping of an iterative process by the criterion of the minimum of the fitness function and determination of the optimal value of a threshold level. We presented the generalized scheme of the method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth based on the method of artificial bee colony (Fig. 2).

We substantiated the choice of the fitness function for segmentation of the optical-electronic image of the on-board system of remote sensing of the Earth. The typical model images were considered, when an object and a background are separated (Fig. 3, *a*) and an object and a background are not separated (Fig. 3, *b*). It was established that it is advisable to choose a sum of variance of brightness of segments of a segmented image as a fitness function. We presented a form of a fitness function for typical model images (Fig. 5). We formulated the optimization problem of selection of a threshold of segmentation of an optical-electronic image (expressions (15) to (20)). The optimization problem was solved by the method of iterative calculations.

We carried out experimental studies on the segmentation of the typical optical-electronic image of the on-board system of remote sensing of the Earth by the developed method. The image from the spacecraft Ikonos was selected as a typical image. This image is a typical structured image of on-board systems for remote sensing of the Earth. Experimental studies confirmed efficiency of the developed segmentation method based on the method of artificial bee colony (Fig. 8). There are possible objects of interest identified in the segmented image (Fig. 8) as an example, namely: oil or fuel containers for planes, planes that survived a strike, damaged or destroyed planes, etc.

We performed evaluation of the quality of segmentation of a typical optical-electronic image of the on-board system of remote sensing of the Earth by the developed method and by the known segmented methods. We selected Otsu method, Canny method, k-means (k=2, 3, 4) method, Random forest method, and ACO method as the known methods of segmentation. A visual assessment of segmentation quality was performed (comparison of Fig. 7 and 8). It was established that objects of interest (oil or fuel containers for planes, planes that survived a strike, damaged or destroyed airfields) are better defined visually in Fig. 8. We performed calculation and calculated errors of the first type and the second type (21), (22) for the quantitative evaluation of the segmentation quality by the developed method. It was established that application of the developed method of segmentation of an image of on-board systems of remote sensing of the Earth will reduce the value of segmentation errors of the first type and the second type on average by the magnitude from 7 % to 33 % (Table 1).

The main disadvantage of the developed method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth is the need for a significant computation resource.

Directions for further research are:

– processing of a large-scale sequence of images of on-board systems of remote sensing of the Earth;

– research of the method under conditions of the influence of the main distorting factors (rotation of an image at different angles, changes in scale and an effect of noise of different origin).

6. Conclusions

1. We developed the method of segmentation of optical-electronic images of on-board systems of remote sensing of the Earth. It was proposed to apply the artificial bee colony method to determine a segmentation threshold. The essence of the method of artificial bee colony consists in determination of initial positions of agents, their migration, determination of conditions for the stopping of an iterative process by the criterion of the minimum of a fitness function and determination of the optimal value of a threshold level.

2. We substantiated the choice of a fitness function for segmentation of an optical-electronic image of the on-board system of remote sensing of the Earth. It was established that it is advisable to choose a sum of variance of brightness of segments of a segmented image as a fitness function. We formulated the optimization problem of selection of a threshold of segmentation of optical-electronic image.

3. We carried out experimental studies on segmentation by the developed method of a typical optical-electronic image of on-board system of remote sensing of the Earth. Experimental studies confirmed efficiency of the developed segmentation method. There were possible objects of interest identified (oil or fuel tanks for planes, planes that survived the strike, damaged or destroyed airfields, etc.) in the segmented image as an example.

4. We performed evaluation of the segmentation quality of a typical optical-electronic image of the on-board system of remote sensing of the Earth by the developed method and by known methods of segmentation. It was established that application of the developed method of segmentation of an image of on-board systems of remote sensing of the Earth will increase the visual quality of detection of objects of interest and reduce a value of segmentation errors of the first type and the second type on average by a magnitude from 7 % to 33 %.

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