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METHOD FOR DETERMINING ELEMENTS OF URBAN INFRASTRUCTURE OBJECTS BASED ON THE RESULTS FROM AIR MONITORING

Запропоновано двоетапний метод визначення елементів об'єктів міської інфраструктури на зображеннях з систем повітряного моніторингу. На першому етапі методу запропоновано на зображеннях визначати контури об'єктів. У якості методу визначення контурів обрано удосконалений метод Канні. Розглянуті основні етапи удосконаленого методу Канні щодо визначення контурів об'єктів на зображеннях з систем повітряного моніторингу. На другому етапі запропоновано використання перетворення Хафа.

Визначені особливості методу визначення елементів об'єктів міської інфраструктури на кольорових зображеннях з систем повітряного моніторингу. На відміну від відомих, у методі враховані особливості формування зображення з систем повітряного моніторингу, виділяються кольорові канали, у кожному кольоровому каналі виділяються контури та геометричні примітиви, проводиться зворотне об'єднання кольорових каналів та визначаються елементи об'єктів міської інфраструктури у просторі вихідного зображення.

Наведені результати застосування методу визначення елементів об'єктів міської інфраструктури на типовому кольоровому зображенні з системи повітряного моніторингу. На результуючому зображенні для прикладу визначені елементи об'єктів міської інфраструктури: дороги, будинки, вулиці, елементи забудови тощо.

Проведена візуальна оцінка якості обробки типового кольорового зображення з системи повітряного моніторингу. Розраховані помилки першого та другого роду. Встановлено, що застосування двоетапного методу визначення елементів об'єктів міської інфраструктури на зображенні з системи повітряного моніторингу дозволить підвищити якість обробки оптико-електронних зображень. При цьому помилки визначення елементів об'єктів міської інфраструктури першого та другого роду знижені в середньому на величину 13 %

Ключові слова: бортова система спостереження, елементи об'єктів міської інфраструктури, метод Канні, перетворення Хафа

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1. Introduction

It is known that application of aeronautical means, such as space systems, aircraft, drones, etc., makes monitoring of urban infrastructure most effective [1, 2]. It is possible to use information acquired from air monitoring systems in various fields [3–7]:

– land use (creation of land cadasters, inventory of land plots, land delineation);

– architecture (design of general layouts, landscape design);

– cartography (creation of a city map);

– urban planning (city development planning, urban infrastructure development planning);

– design and construction (design of highways and railroads, general layouts, electrical and pipeline networks);

– military affairs (planning of hostilities in a city, reconnaissance);

– demography and statistics (demographic and statistical analysis), etc.

The objects of urban infrastructure are streets, buildings, structures, bridges, highways, roads, transport interchanges, railways, oil and gas pipelines, power lines, etc. [6–8]. The information on objects of an urban infrastructure obtained from air monitoring systems gives possibility to evaluate changes in a city quickly and to keep updating information for geoinformation systems [5]. Determination of elements of urban infrastructure objects is important for mapping and cadastral accounting of real estate objects, state accounting of buildings, structures, premises, objects of unfinished construction, municipal geoinformation systems, etc. [3, 6–7]. People apply air monitoring information widely to manage railway infrastructure. Development of methods for monitoring, evaluation and control of the state of surface facilities, including elements of urban infrastructure objects, is expedient [5, 9]. Identification of elements of urban infrastructure objects is also expedient for transformation of paper archives of topographic plans of territories into digital form. The major time expenditure takes the stage of vectorization of selected elements of urban infrastructure objects and geographic mapping of them to the digital map of an area [7]. Image vectorization based on definition of elements of urban infrastructure objects is also relevant when creating mobile robotic complexes. Such a problem arises when it is necessary to transmit information for its further analysis [1, 2, 10]. Vectorization of contours in images gives possibility to transmit only the characteristic information in a compact form, and not all the image, which increases the data transfer rate significantly [1, 2, 10].

Therefore, it is important to develop a method for determination of elements of urban infrastructure objects on images acquired from air monitoring systems, taking into account contrast and shape of elements.

2. Literature review and problem statement

Let us carry out a brief analysis of known methods for determination of contours and boundaries of objects of interest in heterogeneous images, including images made by air monitoring systems.

Authors of paper [7] proposed methods of connection (stitching) of contours and comparison using a pattern. The disadvantages of the methods are complexity of practical implementation, high calculational costs and a need to use a priori information about the original image.

Work [9] proposed methods for digital image processing based on the use of a two-dimensional differential Laplace scalar operator. The main disadvantages are inability to determine the direction of a border and not highlighting, but only underlining of the difference in brightness.

Authors of work [10] proposed gradient methods to determine boundaries. They calculate the complete vector of an image gradient. The main disadvantages are complexity of resolution of the Bayesian problem and a need for a priori knowledge of conditional probabilities of gradient values.

The authors applied various methods of spatial differentiation (Sobel, Previt, Roberts, Wallis, sequential masking, etc.) to determine boundaries of an image in work [10]. The main disadvantages of the methods are presence of discontinuities, dots and strokes, which form an interfering background, a need to know the initial approximation to the desired boundary and considerable calculational cost. The disadvantage of sequential masking methods is a reduction in the contrast of an image and blurriness of an image.

The disadvantage of the Laplacian-Gaussian (LoG) method [10] is the non-directionality of the Laplace and Gauss operators. Due to this, the method sensibly responds to changes in brightness in a parallel direction, which reduces the signal-to-noise ratio.

Paper [11] proposed the use of the active contour method. The disadvantages of the method are high accuracy of initial approximations and considerable calculational cost.

Authors of work [12] used the multi-tasked convolutional neural RoadNet network (Wuhan University, China) to determine road networks in images made by air monitoring systems. However, the use of the RoadNet network can identify road networks only. There are some difficulties in identification of other elements of urban infrastructure. A network needs training, accurate initial values, etc.

Work [13] proposed application of neural networks for mapping and land cadaster using images made by World View-2 system (DigitalGlobe, United States). The methods proposed in [13] solved problems for rural areas. The application of methods [13] for definition of elements of urban infrastructure is difficult.

Authors of paper [14] proposed to use the ant method of thematic segmentation to determine contours in an image. The main disadvantage of the method is over-segmentation, that is, the presence of a large number of contours of small objects ("rubbish" objects) in a resulting image.

Paper [15] proposed using multiscale processing of images made by air monitoring systems according to the ant algorithm. The main disadvantage of the method is marking out of areas that may be objects of interest, not contours.

Work [16] proposed the method of artificial bee colony for thematic segmentation of optical-electronic images. The work outlines the essence of the method. The disadvantage of the method is a considerable calculational resource.

Authors of work [17] advanced the results from work [16]. They formulated optimization problem of segmentation of images made by air monitoring systems by the method of artificial bee colony. The disadvantage of the method is that it defines not contours of objects of interest, but areas, which are potential objects of interest.

Thus, the resolution capability of modern air monitoring systems makes it possible to identify urban infrastructure objects by known methods [9–17]. The aim of the most of known methods [9–17] is definition of contours and boundaries of objects in heterogeneous images, including images made by air monitoring systems. The basis of operation of the methods is definition of contours and boundaries due to differences in brightness. The methods are effective for processing of tone images with clear blur-free boundaries. But if one processes a color image, for example, in the Red-Green-Blue (RGB) color space, there will be conversion of a color image into tone one without taking into account information in each color channel. And then the method will determine contours and boundaries. One may lose information on each color space channel. In addition, the known methods may not determine the direction of a border; they underline the difference in brightness only. They require a priori knowledge of values of the gradient and have breaks under the influence of background noise and blurred boundaries. They reduce the contrast of an image, etc.

The base of another group of known methods [18–21] is the fact that urban infrastructure objects consist of geometric primitives (straight lines, circles, etc.). Such methods operate according to the Radon integral vector transform [18] and the Hough transform [19–21]. The mentioned methods provide a qualitative determination of geometric primitives in images made by air drones, for example, for detection of a power line in a forest area [19].

Authors of work [18] use the Radon integral vector transform for determination of geometric primitives in images. The disadvantage of the Radon transform for definition of elements of urban infrastructure objects is its calculational complexity. The number of mathematical operations for geometric primitives and geometric objects of a complex shape does not differ.

Authors of paper [19] used a partial case of the Radon transform, that is a Hough transform [21] for determination of geometric primitives in images made by air drones for detection of a power line in forest area. Application of the Hough transform is appropriate for definition of geometric primitives in images, which are simple in terms of location of objects. These can be images of woodlands, agricultural fields, rivers, seas, oceans and more. Hough transform defines a large number of "rubbish" objects in images with complex structures of a city. This fact affects a quality of further decryption of urban infrastructure images significantly.

Paper [20] proposed to use the Canny boundary selection method to determine boundaries in an image. The Canny method is the most effective method for determination of boundaries. The Canny method provides a high probability of detection and high accuracy of localization. The disadvantage of the Canny method is destruction of boundaries at junction points.

Computer-based remote sensing decrypting technologies use specialized software [17] for Earth sensing. The most common software tools for processing of Earth remote sensing materials are ERDAS IMAGINE, TNTmips, ER Mapper, ENVI, GRASS, INTERGRAPH, Arc View, ScanViewer, IMAGE Transformer, MODIS Processor, IRS Processor, ScanMagic, SCANEX NERIS, LESSA and others. Some software tools do not resolve tasks of identification of elements of urban infrastructure objects at all; others use well-known methods for identification of boundaries and contours.

The analysis showed that we can't apply the existing methods of identification of object boundaries and contours directly to definition of elements of urban infrastructure objects in images made by air monitoring systems. They do not take into account features of formation of images made by air monitoring systems and their complexity.

Authors of paper [22] used the methods of determination of contours, boundaries and transforms of Radon and Hough consistently in processing of tone medical images for determination of geometric primitives. The results of [22] make it possible qualitative determination of geometric primitives in medical images. However, medical images [22] are tone only; they differ significantly from images made by air monitoring systems by their structure.

Images made by air monitoring systems are complex [17] and contain a large number of heterogeneous objects. Therefore, it is necessary to take into account complexity of structured images made by air monitoring systems in application of the well-known methods for determination of boundaries, contours, and Radon and Huff transforms for identification of elements of urban infrastructure objects. The identification of elements of urban infrastructure objects means definition of geometric primitives of these objects. We should take into consideration that elements of urban infrastructure objects are contrast and consist of simple geometric primitives. This fact is a decisive feature of elements of urban infrastructure objects. We set out the task to develop a method for identification of elements of urban infrastructure objects in tone and color images made by air monitoring systems using sequentially contours, boundaries, and Hough transform methods in further study.

3. The aim and objectives of the study

The objective of the study is to develop a method for identification of elements of urban infrastructure objects in tone and color images made by air monitoring systems.

It is necessary to solve the following problems to achieve the objective:

– presentation of the basic principles and stages of the method for determination of elements of urban infrastructure objects in tone images made by air monitoring systems;

– identification of features of the method being developed for identification of elements of urban infrastructure objects in color images made by air monitoring systems;

– processing of a typical color image made by an air monitoring system to identify elements of urban infrastructure objects;

– evaluation of errors of first and second kinds in identification of elements of urban infrastructure objects in a typical color image made by an air monitoring system.

4. Materials of the study on determining elements of urban infrastructure objects according to the results from air monitoring

4. 1. Basic principles and stages of the method for determination of elements of urban infrastructure objects in tone images acquired from air monitoring systems

Identification of elements of urban infrastructure objects in the image (1):

$$f(\mathbf{X}, \mathbf{Col}), \tag{1}$$

where $\mathbf{X}=(x, y)$ is the vector of pixel coordinates of the image; $\mathbf{Col}$ is the color space of the image representation provides definition of $\mathbf{Q}(\mathbf{X}, \mathbf{P})$ contours with $\mathbf{P}(p_1, p_2, ..., p_N)$ parameter vector.

We can see from $\mathbf{Q}(\mathbf{X}, \mathbf{P})$ contour notation that the function, which describes the contour, depends on two parameters. They are $\mathbf{X}$ pixel coordinates characterized by brightness and geometric parameters of $\mathbf{P}$ contour. As we noted above, elements of urban infrastructure objects are contrast and consist of simple geometric primitives. Therefore, we consider the method for determination of elements of urban infrastructure objects as a two-step method. The first stage analyzes the decrypting feature – brightness. The second stage analyzes the decrypting feature – the geometric shape and parameters of **P** element of the urban infrastructure object.

Fig. 1 shows a general diagram of the method for determination of elements of urban infrastructure objects in images made by air monitoring systems. The diagram represents the sequence of actions of the proposed method.

$f(\mathbf{X}, \mathbf{Col})$ function transforms into $f(\mathbf{X})$ function, where $f(\mathbf{X})$ is the brightness of the tone image, which changes in the interval of [0...255], in the first stage of the analysis of the brightness and the definition of contours in the tone image. There is a contour point at **X** point when the absolute value of the discrete gradient exceeds a certain threshold level $m>0$ (expression (2)):

$$|\Delta f(\mathbf{X})|=|f(\mathbf{X}+\mathbf{I})-f(\mathbf{X})|\geq m <=> \{\mathbf{X}\epsilon\mathbf{Q}(\mathbf{X}, \mathbf{P})\}, \quad (2)$$

where **I** is the unit matrix.

We use the advanced Canny method for the first stage [17]. The first step of the method for determination of elements of urban infrastructure objects in images made by air monitoring systems includes the following blocks (Fig. 1).

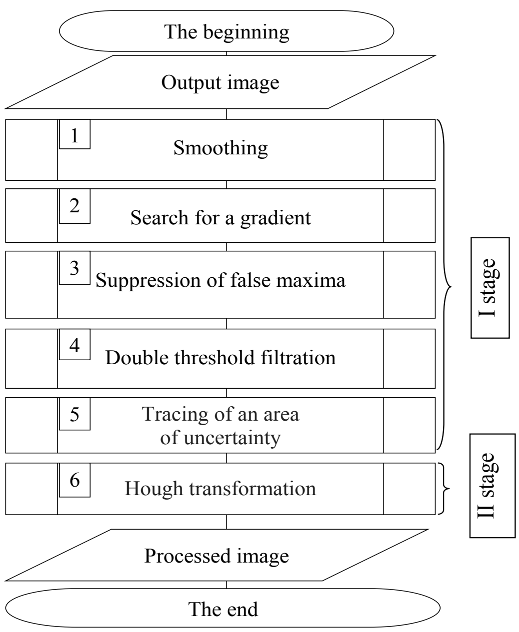

Fig. 1. General diagram of the method for determination of elements of urban infrastructure objects in images made by air monitoring systems

Block 1. Smoothing. It is necessary to reduce the effect of noise on boundary determination. The Gaussian filter is used for it (3):

$$f(x,y)=\frac{1}{2\pi\sigma}e^{\left(-\frac{x^2+y^2}{2\sigma^2}\right)}, \quad (3)$$

where σ is the blur parameter.

One should choose the value of the blur parameter to provide the highest noise suppression. We use the larger value of the parameter to highlight large contours, and the less one to highlight thin contours and small details.

Block 2. Search for a gradient. One uses the Sobel operator to determine the gradient in the image after the Gaussian filter (3). The basis of Sobel's transformation is the assumption that the brightness difference function becomes much larger on borders. One can conclude from this assumption that it is sufficient to differentiate $f(x, y)$ brightness functions (4), (5) to find the borders:

$$\frac{\partial f(x,y)}{\partial x}=\Delta x=\frac{f(x+\mathrm{d}x,y)-f(x,y)}{\mathrm{d}x}, \quad (4)$$

$$\frac{\partial f(x,y)}{\partial y}=\Delta y=\frac{f(x,y+\mathrm{d}y)-f(x,y)}{\mathrm{d}y}. \quad (5)$$

One can measure dx and dy between two points in pixels by expressions (6), (7) in discrete images:

$$\Delta x=f(i+1,j)-f(i,j), \quad (6)$$

$$\Delta y=f(i,j+1)-f(i,j). \quad (7)$$

The expression (8) determines the value of G gradient:

$$G=\sqrt{(\Delta x)^2+(\Delta y)^2}, \quad (8)$$

and we determine θ direction from expression (9):

$$\theta=\arctan\left(\frac{\Delta x}{\Delta y}\right). \quad (9)$$

We evaluate the gradient using masks in expressions (8), (9):

$$\Delta x=\begin{pmatrix}-1 & 1\\ 0 & 0\end{pmatrix}, \quad (10)$$

$$\Delta y=\begin{pmatrix}-1 & 0\\ 1 & 0\end{pmatrix}. \quad (11)$$

The major disadvantage of using (10) and (11) masks in the classic Canny method [17] is a large number of errors due to noise. In addition, the use of masks of the pair order in the classic Canny method [17] does not make it possible to carry out evaluation based on a pixel centered on the mask.

Unlike the classic Canny method [17], we use the Sobel operator with masks (12), (13) for evaluation of the gradient:

$$K_{G_x}=\begin{pmatrix}-1 & 0 & 1\\ -2 & 0 & 2\\ -1 & 0 & 1\end{pmatrix}, \quad (12)$$

$$K_{G_y}=\begin{pmatrix}1 & 2 & 1\\ 0 & 0 & 0\\ -1 & -2 & -1\end{pmatrix}. \quad (13)$$

There is the coefficient 2 used for the average elements in expressions (12), (13) (in comparison to (10), (11)). In contrast to the classic Canny method [17], we reduce the smoothing effect. Values and the direction of a value of G gradient take the forms (14), (15), respectively:

$$G = \sqrt{G_x^2 + G_y^2}, \tag{14}$$

$$\theta = \arctan\left(\frac{|G_x|}{|G_y|}\right). \tag{15}$$

As a result of using the Sobel operator with masks (12), (13), the intensity of each pixel of the output image is equal to the gradient of the brightness vector.

Block 3. Suppression of false maxima. The objective of this stage is to turn "blurred" boundaries into "clear" ones. We achieve this by maintenance of local maxima and removal of everything else. There are the following steps performed for each pixel:

– the rounding of direction of the gradient to the nearest value, which is a multiple of 45° (Fig. 2, *a*);

– if there is the local maximum reached at the current point in the direction of the gradient, then it is part of a boundary;

– otherwise the point is deleted (Fig. 2, *b*).

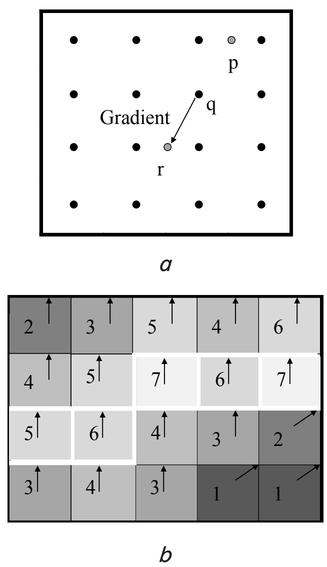

Fig. 2. Search for local maxima: *a* – *p* and *r* maxima are interpolated (deleted); *b* – the principle of suppression of false maxima

Fig. 2, *b* illustrates the suppression principle. All pixels have an upward orientation in Fig. 2, *b*, so we compare the gradient value at these points to the pixels below and above. The pixels outlined by white color in Fig. 2, *b* remain in the output image, the other ones will be suppressed.

Block 4. Double threshold filtration (Fig. 3). Each pixel, which exceeds the upper threshold, is a "strong" pixel. Each pixel, which falls between two thresholds, is a "weak" one. The brightness of "weak" pixels assumes a fixed average value and will be refined in the next stage. Pixels, which are smaller than the lower threshold, are deleted.

The use of a double threshold gives possibility to reduce an effect of noise (due to the upper threshold) and not to lose "tails" (due to the lower threshold).

Block 5. Unlike in the classic Canny method [17], we trace the uncertainty area in the block 5. The task is to isolate groups of pixels, which got an intermediate value in the previous stage, and to assign them to a boundary (if they are connected to one of the boundaries) or to suppress them (otherwise). This block makes it possible to reduce missing of pixels in definition of object contours.

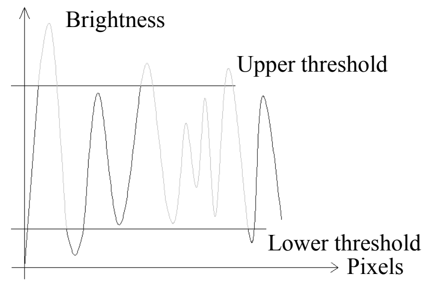

Fig. 3. The use of two thresholds

Thus, we determine contours of objects at the first stage of the method for determination of elements of urban infrastructure objects in images made by air monitoring systems. The main decrypting feature is the brightness of pixels in the image. We choose the advanced Canny method. Unlike the known method, it uses the Sobel operator with masks of (3×3) to evaluate the gradient and it traces the area of uncertainty additionally, which reduces the smoothing effect and missing of pixels in determination of object contours.

The second stage analyzes the decryption feature – the geometric shape and $\mathbf{P}=(p_1, p_2, ..., p_N)$ parameters of elements of the urban infrastructure object. We use the Hough transform for straight lines [21] to determine $(p_1, p_2, ..., p_N)$ parameters at the second stage. One calls $\mathbf{P}=(p_1, p_2, ..., p_N)$ space parametric.

For each (x, y) contour point, we perform the procedure of increasing of the value of all cells of $\mathbf{P}=(p_1, p_2, ..., p_N)$ parametric space with $(p_1, p_2, ..., p_N)$ coordinates, which satisfy equation (16), by one:

$$\mathrm{P}(p_1, p_2, ..., p_N)=P^*(p_1, p_2, ..., p_N)+1$$
$$\forall\ (p_1, p_2, ..., p_N)\text{: } \mathbf{Q}(\mathbf{X}, p_1, p_2, ..., p_N)=0, \tag{19}$$

where $\mathrm{P}(p_1, p_2, ..., p_N)$ is the new value of the cell of the parametric space; $\mathrm{P}^*(p_1, p_2, ..., p_N)$ is the previous value of a cell of the parametric space.

The coordinates of cells in the parametric space will generally correspond to the figures in the image after recalculation for all points of the contour.

The elements of urban infrastructure objects generally have the shape of a straight line [6–8]. Therefore, one can represent the equation of a line, which passes through a point with (x,y) coordinates, as (20) (Fig. 4):

$$x\cos(\varphi) + y\sin(\varphi) = \rho, \tag{20}$$

where ρ is the distance from the origin of coordinates to the straight line (a beam); φ is the angle between the abscissa and the beam.

One can represent the parametric space as (21):

$$\mathbf{P}(\rho, \varphi), \tag{21}$$

each its cell has (ρ, φ) coordinates.

Thus, for each (x, y) contour point, we perform the procedure of increasing of the value of all cells of the parametric space (21) with coordinates by equation (22), (x, y):

$$P(\rho, \varphi)=P^{*}(\rho, \varphi)+1 \ \forall \ (\rho, \varphi): \mathbf{Q}(\mathbf{X}, \rho, \varphi)=0, \quad (22)$$

where $P(\rho, \varphi)$ is the new value of a cell of the parametric space; $P^{*}(\rho, \varphi)$ is the previous value of a cell of the parametric space.

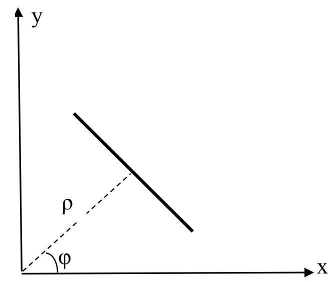

Fig. 4. Parameters of the direct element of urban infrastructure objects

Thus, we consider the method for determination of elements of urban infrastructure objects as a two-step method. The first stage analyzes the decryption feature – brightness. The advanced Canny method was chosen for the analysis. Unlike the known method, it uses the Sobel operator masks of (3×3) sizes to evaluate the gradient and it traces an uncertainty area, which reduces the smoothing effect and missing of pixels in determination of contours of objects.

The second stage analyzes the decryption feature – the geometric shape of an element of an urban infrastructure object. At this point, the Hough method was chosen for the analysis.

One should note that this method is applicable for tone images. Therefore, for further research, let us look at features of the method for determination of elements of urban infrastructure objects in color images made by air monitoring systems.

4. 2. Features of the method being developed for determination of elements of urban infrastructure objects in color images made by air monitoring systems

We have color images made by air monitoring systems presented in the Red-Green-Blue (RGB) color space. This fact is taken into account when determining elements of urban infrastructure objects in color images made by air monitoring systems. In contrast to known methods [9–11] of contour determination, there is recommendation not to proceed to a tone image immediately and then to the binarized image in processing of color images, due to the fact that elements of urban infrastructure objects are in all three RGB color channels at the same time. If object elements are in one color channel only, an element may be of natural origin (for example, river); if objects are in two color channels at the same time, element classification is difficult (this may be, for example, field road, etc.). The above is an additional decryption feature of elements of urban infrastructure objects in color images made by air monitoring systems.

In view of the above, Fig. 5 shows the sequence of actions of the method.

The method involves:

– an input of the output color image: $f(\mathbf{X})$ ($\mathbf{X}=(x, y)$);

– definition of color channels in the output $f(\mathbf{X})$ color image: $f_R(\mathbf{X})$, $f_G(\mathbf{X})$, $f_B(\mathbf{X})$ (where $f_R(\mathbf{X})$, $f_G(\mathbf{X})$, $f_B(\mathbf{X})$ are the images by Red, Green, and Blue color channels, respectively);

– definition of the brightness channel in each color channel of the output image: $f_R(\mathbf{X})$, $f_G(\mathbf{X})$, $f_B(\mathbf{X})$;

– determination of elements of urban infrastructure objects in images made by air monitoring systems in each color channel by the method (Fig. 1) and obtaining of images by each color channel: $fs_R(\mathbf{X})$, $fs_G(\mathbf{X})$, $fs_B(\mathbf{X})$ (where $fs_R(\mathbf{X})$, $fs_G(\mathbf{X})$, $fs_B(\mathbf{X})$ are the images with defined elements of urban infrastructure in Red, Green, and Blue color channels, respectively);

– back transfer to RGB color model (integration of color channels);

– obtaining of the processed $fs(\mathbf{X})$ image.

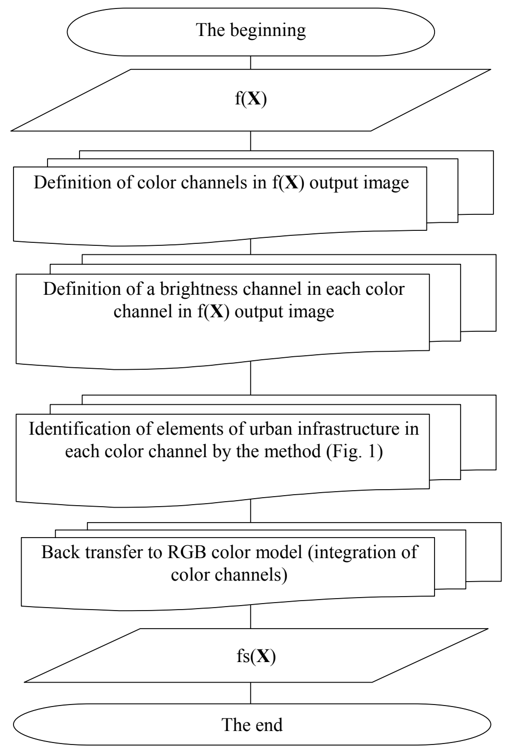

Fig. 5. The method for determination of elements of urban infrastructure objects in color images made by air monitoring systems

Therefore, there are the following features of the method for determination of elements of urban infrastructure objects in color images made by air monitoring systems. Unlike the known ones, the method takes into account features of formation of images made by air monitoring systems. It highlights color channels and marks out contours and geometric primitives in each color channel. It re-integrates color channels and identifies elements of urban infrastructure objects in the space of an output image.

4. 3. Results of processing a typical color image made by an air monitoring system for determination of elements of urban infrastructure objects

Fig. 6 shows the image acquired from Ikonos spacecraft air system (DigitalGlobe, United States) [14]. The image is in RGB color space. The image size is (3,000×4,000) pixels. The image (Fig. 6) is a typical image of a city with elements of urban infrastructure objects. Therefore, there is only one typical image, which takes into account all features of city images made by air monitoring systems, in the experimental studies.

Fig. 6. The image acquired from Ikonos spacecraft air system (DigitalGlobe, United States) [14]

Fig. 7 shows the implementation of the first stage of the method for determination of elements of urban infrastructure objects according to the results of air monitoring.

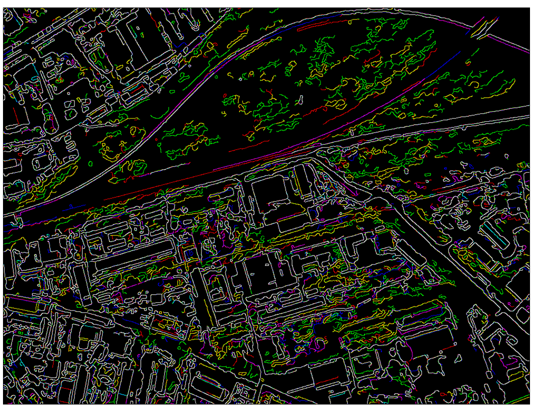

Fig. 7. The image after the first stage of the method for determination of elements of urban infrastructure objects according to the results of air monitoring

The first stage analyzed the decryption feature – brightness – and used the advanced Canny method.

Fig. 8 shows the image after the second stage of the method for determination of elements of urban infrastructure objects according to the results of air monitoring.

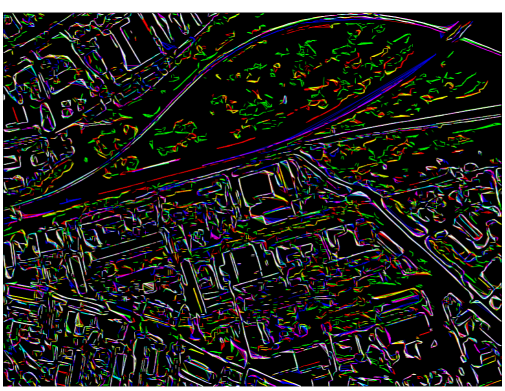

Fig. 8. The image after the second stage of the method for determination of elements of urban infrastructure objects according to the results of air monitoring

Fig. 7, 8 show images in pseudo-colors after integration of color channels for visual demonstration of the method. The rules for integration of color channels are as follows:

– if a pixel of the image relates to the boundary in all three channels of the Red-Green-Blue color space at the same time, this pixel becomes white;

– if a pixel of the image relates to the boundary in the Red channel and there is no determination of a boundary in the Green and Blue channels, this pixel becomes red;

– if a pixel of the image relates to the boundary in the Blue channel and there is no determination of a boundary in the Green and Red channels, the pixel becomes blue;

– if a pixel of the image relates to the boundary in the Green channel and there is no determination of a boundary in Red and Blue channels, it becomes green;

– if a pixel of the image relates to the boundary in the Green and Blue channels at the same time and there is no determination of a boundary in the Red channel, this pixel becomes blue;

– if a pixel of the image relates to the boundary in the Red and Blue channels at the same time and there is no determination of a boundary in the Green channel, the pixel becomes purple;

– if a pixel of the image relates to the boundary in the Red and Green channels at the same time and there is determination of a boundary in the Blue channel, the pixel becomes yellow;

– if there are no boundaries defined in all three Red-Green-Blue channels at the same time, the pixel becomes black.

Fig. 9 shows the processed image for demonstration of the use of the additional decryption feature for determination of elements of urban infrastructure objects in color images.

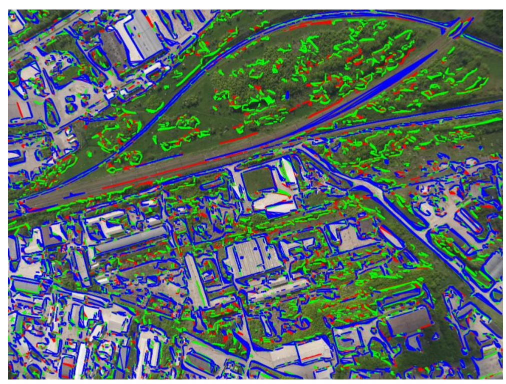

Fig. 9. The image with identified elements of urban infrastructure objects taking into account their presence in processing channels

We obtained colors in Fig. 9 according to the following rules:

– if there is a geometric primitive in all three channels of the color space of the RGB image representation (Red-Green-Blue) at the same time, the pixel is blue;

– if there is a geometric primitive in one of the three channels of the color space of the RGB image representation (Red-Green-Blue), the pixel is green;

– if there is a geometric primitive in two channels at the same time and it is absent in another channel in the color space of the RGB image representation (Red-Green-Blue), the pixel is green.

Fig. 10 shows only the identified elements of urban infrastructure objects, which are of artificial origin. Such elements are blue in Fig. 9.

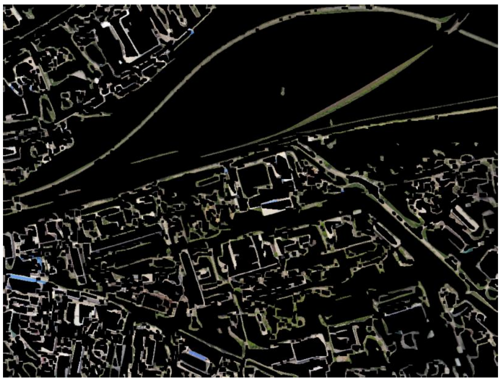

Fig. 10. The identified elements of urban infrastructure objects

Decryption of the defined elements of urban infrastructure objects, their identification, thematic classification and more are the subject of further research and remain beyond the scope of this study.

4. 4. Evaluation of errors of first and second kinds in determination of elements of urban infrastructure objects in a typical color image made by an air monitoring system

We selected errors of first and second kinds as indicators for the evaluation of the quality of determination of elements of urban infrastructure objects in a typical color image made by an air monitoring system. The maximum likelihood criterion, which follows from the generalized minimum risk criterion [23], determines errors of first (α_1) kind and second (β_2) kinds in determination of elements of urban infrastructure objects. We calculate errors of first α_1 and second kind β_2 (23), (24) in determination of elements of urban infrastructure objects, respectively [23]:

$$\alpha_1 = \frac{S_1\left(fs(\mathbf{X})\right)}{S_2\left(f(\mathbf{X})\right)}, \qquad (23)$$

$$\beta_2 = 1 - \frac{S_3\left(fs(\mathbf{X})\right)}{S_4\left(\left(f(\mathbf{X})\right)\right)}, \qquad (24)$$

where $S_1(fs(\mathbf{X}))$ is the area of background zones mistakenly assigned to elements of urban infrastructure in $fs(\mathbf{X})$ image; $S_2(f(\mathbf{X}))$ is the area of background zones of the output $f(\mathbf{X})$ image; $S_3(fs(\mathbf{X}))$ is the area of correctly defined elements of urban infrastructure in $fs(\mathbf{X})$ image; $S_4(f(\mathbf{X}))$ is the area of urban infrastructure elements in the output $f(\mathbf{X})$ image.

We perform calculations by expressions (23), (24) under the same conditions, the same signal-to-noise ratio for the methods for determination of elements of urban infrastructure objects, but by the advanced Canny method (Fig. 7) and by the two-stage method (Fig. 10). We calculate $S_1(fs(\mathbf{X}))$ and $S_3(fs(\mathbf{X}))$ values for evaluation of errors of first and second kinds in Fig. 7, 10. There are $S_2(f(\mathbf{X}))$, $S_4(f(\mathbf{X}))$ values calculated in the output image (Fig. 6).

Table 1 gives the values of errors of first and second kinds calculated for expressions (23), (24) for the Canny method (Fig. 7) and the developed method (Fig. 10).

The analysis of data from Table 1 indicates an improvement in the quality of processing of images made by air monitoring systems when using the developed method for determination of elements of urban infrastructure objects. Errors of first and second kind in determination of elements of urban infrastructure objects reduced by 13 % on average.

Table 1

Evaluation of errors of first and second kinds in determination of elements of urban infrastructure objects by various methods

Methods of determination of elements of urban infrastructure objects	Canny	The developed method
α_1, %	22.19	9.30
β_2, %	26.71	13.22

5. Discussion of the results of development of the method for determination of elements of urban infrastructure objects in images made by air monitoring systems

We have defined the essence of the method for determination of elements of urban infrastructure objects in images made by air monitoring systems. The method consists of two stages. The first stage analyzes the decryption feature – the brightness. The advanced Canny method was chosen for the analysis. In contrast to known method, it uses the Sobel operator with masks of (3×3) sizes to evaluate the gradient, and it traces an uncertainty area additionally, which reduces the smoothing effect and missing of pixels in determination of contours of objects. The second stage analyzes the decryption feature – the geometric shape of an element of an urban infrastructure object. At this point, we chose the Hough method for analysis.

The features of the method for determination of elements of urban infrastructure objects in color images made by air monitoring systems are as follows. Unlike the known methods, the method takes into account features of formation of images made by air monitoring systems. It highlights color channels and marks out contours and geometric primitives in each color channel. It re-integrates color channels and identifies elements of urban infrastructure objects in the space of an output image. It takes into consideration an additional decrypting feature of elements of urban infrastructure objects in color images in RGB color space. The elements of urban infrastructure objects locate in all three RGB color channels at the same time. If elements of objects are in one color channel only, the element may be of natural origin; if elements of objects are in two color channels at the same time – the classification of elements is difficult.

Experimental studies to identify elements of urban infrastructure objects were carried out. The results of the method of determination of elements of urban infrastructure objects after each stage were given. We identified elements of urban infrastructure objects in the resulting image, such as houses, roads, buildings, bridges, and more, as an example.

We evaluated the quality of determination of elements of urban infrastructure objects in a color image made by an air monitoring system by the proposed method and by the Canny method. The errors of first and second kinds were calculated in determination of elements of urban infrastructure objects for the quantitative evaluation of the quality of processing. It was established that the use of the developed method for determination of elements of urban infrastructure objects reduces errors of first and second kinds in determination of elements of urban infrastructure objects by 13 % on average.

The main disadvantage of the developed method for determination of elements of urban infrastructure objects in images made by air monitoring systems is a need for a significant calculational resource.

For carrying out further research, it is necessary to:

– develop a method of multiscale processing of images made by air monitoring systems;

– calculate information indicators for determination of elements of urban infrastructure objects.

6. Conclusions

1. We have presented the basic principles and stages of the method for determining elements of urban infrastructure objects in tone images acquired from air monitoring systems. The essence of the method is the sequential analysis at the first stage of the decryption feature – brightness, and at the analysis of the decryption feature – the geometric shape of element of an urban infrastructure object at the second stage.

2. The features of the method for determination of elements of urban infrastructure objects in color images made by air monitoring systems are as follows. In contrast to known methods, the method takes into account features of formation of images made by air monitoring systems. It highlights color channels and marks out contours and geometric primitives in each color channel. It re-integrates color channels and identifies elements of urban infrastructure objects in the space of an output image.

3. We carried out experimental studies to determine elements of urban infrastructure objects in a typical color image made by an air monitoring system by the developed method. The experimental studies confirmed productivity of the developed method for identification of elements of urban infrastructure objects. We presented the results of image processing after each stage of the method to make the study clearer. The processed image identifies possible elements of urban infrastructure objects, such as roads, homes, buildings, bridges, and more.

4. We evaluated the quality of the method for determination of elements of urban infrastructure objects in images made by air monitoring systems. It was established that application of the developed method for determination of elements of urban infrastructure objects in a typical image made by an air monitoring system reduces values of errors of first and second kinds by 13 % on average.

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