Generating a Set of Reference Images for Reliable Condition Monitoring of Critical Infrastructure using Mobile Robots

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Abstract. The aim of this work is to reduce the amount of computational cost when monitoring the state of critical infrastructure objects using flying mobile robots equipped with correlation-extreme navigation system, based on minimizing the number of fragments of reference images. The goal is achieved by establishing a minimum permissible degree of correlation between the individual images, which form a set of reference images. The most essential result is substantiation of the approach to formation of a set of selective images based on scene correlation analysis and sufficiency of conservation of correlation connection of images in limits 0.6 ... 0.7. This reduces the amount of computation and extends the operating time of mobile robots while maintaining accuracy. The significance of the obtained results consists in the possibility of solving a complex task of forming a set of reference images, depending on the information content and stochastic conditions of sighting of critical infrastructure objects. The solution of this task will increase efficiency of critical infrastructure objects state control due to optimization of reference images number used in the monitoring process, increase operability, and provide high control reliability in stochastic sighting conditions. The novelty of the work lies in the fact that the method of process formalized description of forming a reference images set to ensure reliable monitoring of critical infrastructure facilities using flying mobile robots for various sectors of the economy, the practical application of which will ensure reliable control and their condition assessment.

Keywords: mobile robot, critical infrastructure object, reference images, navigation system, correlation coupling, optimization.

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Formarea unui set de imagini de referință pentru monitorizarea fiabilă a stării obiectelor de infrastructură critică folosind roboți mobili

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Rezumat. Scopul acestei lucrări este de a reduce costurile de calcul la monitorizarea stărilor obiectelor de infrastructură critică folosind roboți mobili zburători echipați cu un sistem de navigație corelație-extremă bazat pe minimizarea numărului de fragmente de imagini de referință. Acest obiectiv este atins prin stabilirea gradului minim admis de corelare între imaginile individuale care formează un set de imagini de referință. Rezultatul cel mai semnificativ este fundamentarea abordării formării unui set de imagini selective pe baza analizei corelației scenelor și a suficienței menținerii corelației imaginilor în intervalul 0,6 ... 0,7. Acest lucru vă permite să reduceți semnificativ costurile de calcul și să creșteți durata de funcționare a roboților mobili, menținând în același timp precizia necesară. Semnificația rezultatelor obținute constă în posibilitatea rezolvării problemei complexe a formării unui set de imagini de referință în funcție de conținutul informațional și de condițiile stocastice de vizionare a obiectelor de infrastructură critică. Rezolvarea acestei probleme va îmbunătăți eficiența monitorizării stărilor obiectelor de infrastructură critică prin optimizarea numărului de imagini de referință utilizate în procesul de monitorizare, va crește eficiența și va asigura o fiabilitate ridicată a monitorizării în condiții de ochire stocastică. Noutatea lucrării constă în faptul că o descriere oficială a procesului de formare a unui set de imagini de referință a fost elaborate în continuare pentru a asigura monitorizarea fiabilă a obiectelor de infrastructură critică de la roboții mobili zburători.

***Cuvinte-cheie**:* robot mobil, obiect de infrastructură critică, imagini de referință, sistem de navigație, corelare, optimizare.

Формирование совокупности эталонных изображений для осуществления надежного контроля состояний объектов критической инфраструктуры с помощью мобильных роботов

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Аннотация. Целью данной работы является снижение объема вычислительных затрат при осуществлении контроля состояний объектов критической инфраструктуры с помощью летающих мобильных роботов, оснащенных корреляционно-экстремальной системой навигации, на основе минимизации числа фрагментов эталонных изображений, используемых при формировании решающей функции, как результата сравнения изображений. Поставленная цель достигается путем установления минимально допустимой степени корреляционной связи между отдельными изображениями, которые образуют необходимую для мониторинга совокупность эталонных изображений в зависимости от объектового состава, геометрических условий формирования текущих изображений, яркостных, контрастных, структурных (геометрических) информативных параметров, распределение которых представляется в виде соответствующих информативных полей. Наиболее существенным результатом является обоснование подхода к формированию совокупности селективных изображений объектов критической инфраструктуры с использованием инвариантов, полученных на основе корреляционного анализа сцен, и достаточности сохранения корреляционной связи изображений в пределах 0.6… 0.7. Это позволяет существенно снизить объем вычислительных затрат и, соответственно, повысить быстродействие системы вторичной обработки, а также продолжительность функционирования мобильных роботов при сохранении требуемых точностных показателей. Значимость полученных результатов состоит в возможности решения сложной задачи формирования совокупности эталонных изображений, используемых на борту мобильных роботов, в зависимости от объема поступающей информации и стохастических условий визирования объектов критической инфраструктуры. Решение данной задачи позволит повысить эффективность контроля состояний объектов критической инфраструктуры за счет оптимизации числа эталонных изображений, используемых в процессе мониторинга, повысить оперативность и обеспечить высокую надежность контроля в стохастических условиях визирования. Новизна работы заключается в том, что усовершенствован способ формализованного описания процесса формирования совокупности эталонных изображений для обеспечения надежного мониторинга объектов критической инфраструктуры с помощью используемых в разных отраслях народного хозяйства летающих мобильных роботов, практическое применение которых обеспечит надежный контроль и оценку их состояния.

Ключевые слова: мобильный робот, объект критической инфраструктуры, эталонные изображения, система навигации, корреляционная связь, оптимизация.

INTRODUCTION

The task of monitoring the condition of critical infrastructure objects has always been an urgent issue. In conditions of increasing terrorist threat levels and military actions, the need to solve this problem has significantly increased. Critical infrastructure objects primarily include objects of the fuel and energy sector, including the electric power industry, oil and gas industries, nuclear energy, as well as water supply, medicine, transportation, defense, chemical industry, and other areas, whose disruption can lead to national security threats, severe ecological consequences, the population loss of life, destruction of buildings, structures, residential buildings, etc. The complexity of monitoring critical objects is caused by their territorial distribution, heterogeneity of the objects themselves according to geometric, structural, and other information parameters.

Currently, in addition to proactive monitoring methods of critical infrastructure objects, autonomous active methods using flying mobile robots (MR) based on the use of correlation-extreme navigation systems (CENS) are widely used. An essential feature of such MRs is their ability to operate without operator intervention over significant distances in remote and inaccessible areas, regardless of the season, time of day, and weather conditions. This is achieved by using multispectral sensors to extract information (to) obtain high-quality current images of controlled objects and their elements, as well as a set of reference images of critical infrastructure objects used on board for subsequent identification and assessment of their conditions.

It is evident that the diversity of monitoring perspectives and the influence of natural stochastic factors on the MR functioning will result in a mismatch between the current images produced and the reference images stored aboard. The desire to reduce this mismatch necessitates the use of a significant number of reference images aboard the MR that consider all possible conditions under which current images can be obtained. However, this approach is technically impractical as it increases the volume of image comparison operations required to find the best match. As a result, such an approach leads to a decrease in the MR functional capabilities when monitoring critical infrastructure objects at the expense of a deterioration in the high-speed performance of the secondary processing system of CENS, increased energy consumption, which in turn slows down the process of making decisions about their condition.

One possible direction for the MR effective use in monitoring critical infrastructure objects is to form the minimum permissible set of reference images that ensure the required level of accuracy and reliability of the control system. In this context, the question arises as to which method should be used to form the required set of reference images that will provide the necessary performance indicators.

Several directions for improving the efficiency of using MR for monitoring tasks are known. However, this article will be focused on the formation of a set of reference images for reliable monitoring of critical infrastructure objects. This will be achieved by establishing the minimum permissible degree of correlation between individual images. Such images form the necessary set of reference images for monitoring, depending on the object composition, geometric conditions for forming current images, brightness, contrast, and structural (geometric) informative parameters.

Let us consider the known approaches to solving the problem of forming reference images for MR equipped with a CENS.

PUBLISHED LITERATURE ANALYSIS

Tarshin V.A. et al. (2015) proposed a method for forming a reference image based on constructing a fractal analysis field, which allows for operational assessment of the informativeness of the image. The method was developed for forming individual images without considering their possible use in forming a set of reference images.

J.C. Rodríguez-Quiñonez et al. (2017) proposed a method for improving the accuracy of 3D distance measurement in stereo vision systems using optimization methods and the optoelectronic channel for forming current images. The use of the brightest stationary objects ensures an increase in measurement accuracy in perspective and scale images. The interrelation between individual images was not considered.

M. Ivanov et al. (2019) improved the method for determining the coordinates of reference objects and mobile robots and calculating the resulting errors. They considered the directions and magnitudes of external influences on unmanned aerial vehicles that affect the deviation from the calculated trajectory of movement.

Yu Ishihara and Masaki Takahashi (2022) investigated the prediction of future images for mobile robot navigation based on alignment with the sighting surface with multiple bright objects. They selected a predictive image model using the alignment object selection on the high object saturation image. However, the authors did not pay sufficient attention to the study of the interdependence of object brightness on the behavior of the mobile robot.

Leonardo A.F. Fernandes and Manuel M. Oliveira (2008) reviewed approaches to object contour detection and localization on images using the Hough transform.

Fursov V. A., et al. (2013) studied the effect of scale distortions on the object localization process. However, the study was only performed on a single reference image.

S. Maji and J. Malik (2009) presented results of optimizing the object detection procedure on images.

Katulev A. N., et al. (2014) proposed an object detection method using optoelectronic systems without a priori information on the background-target scene.

V. V. Gnilitskii et al. (2010) solved the problem of localizing a given object on an aerial image of a complex three-dimensional ground scene.

R. Bogush and S. Maltsev (2007) proposed using a minimax similarity criterion between two images to form a unimodal decision function.

A.A. Potapov (2013) presented results of using fractal analysis theory for object localization on images of different types.

Trefilov P.M. (2019) showed the feasibility of using platform-less inertial navigation systems (PINS) in unmanned aerial vehicles (UAVs) for monitoring various territories. The physical and algorithmic methods for improving PINS were considered. It was shown that the physical method allows reducing the rate of error accumulation but is unable to eliminate it completely. The application of algorithmic methods based on integration with other measuring systems allows reducing PINS errors. It is noted that satellite navigation systems and technical vision systems can be used for integration with PINS, which can significantly increase the accuracy of UAV navigation.

Scaramuzza D., et al. (2014) presented the results of an analysis of technical issues encountered during the development and testing of an autonomous navigation system. Experimental results demonstrating the autonomous navigation of three micro air vehicles (MAVs) in an unknown environment without GPS, but with the use of 3-D mapping and optimal coverage are presented. A limitation of the study is the complete absence of information on the potential use of the proposed approach for the object state monitoring and reference image formation tasks.

Kostyashkin L.N., et al. (2014) examine approaches to solving key tasks in the development of a combined vision system for aviation. It combines the best properties and functional characteristics of two systems: an enhanced vision system that forms an improved and combined image from several multispectral sensors of a technical vision system, and a synthesized vision system that forms an image of a virtual model of the terrain based on a digital map of the terrain, navigation, and piloting parameters of the UAV. The advantage of the work is the development of algorithmic methods for reducing the complexity of the task of image alignment based on geometric alignment, the necessity of which is associated with map and navigation errors, and the visualization of geometrically aligned images considering the stage of flight task execution and visibility conditions. The disadvantage of the work is the inability to use the developed methods without the participation of a pilot.

Loginov A.A., et al. (2015) considered the issue of reducing computational complexity of combining heterogeneous images in an aircraft's combined vision system. The strength of the work is the proposed solutions that allow reducing the computational complexity of correlation-extremal registration to enable real-time performance. To eliminate the course search, the authors proposed to create large-sized terrain reference images. To avoid pitch and roll search, they suggested using the horizon line or non-correlation registration for pitch. The main idea of non-correlation registration for pitch and roll is to find the real horizon line and combine it with the synthesized one. The limitation of the work is the practical application on unmanned aerial vehicles at low altitudes due to the impracticality of using large-sized reference images and the inability to determine the horizon line during steep trajectories.

Elesina S. and Lomteva O. (2014) presented the results of a study on a genetic algorithm aimed at obtaining optimal settings for its use in combined technical vision systems. The feasibility of using extended angles of reference images in the search for global extremes was shown. It was shown that using this approach, the system's performance increases by 5 times. However, the authors did not consider the possible influence of perspectives of reference and flowing images on real-time implementation, which is a disadvantage.

Yeromina N., et al. (2018a) proposed a method for generating a set of reference images for high-precision navigation of mobile robots. A disadvantage of the developed method in this work is its limited applicability to solving the navigation problem of mobile robots moving along trajectories without significant changes in altitude and viewing angles.

Yeromina, et al. (2021a) justified the need for a new approach to selecting a reference image from the set of images on board when performing localization of aircraft equipped with CENS. The results of developing a model for describing the process of forming the decision function because of comparing the current image formed by the secondary information processing system based on the available set of reference images are presented. Using this model, the task was formulated to develop a method and algorithm for rational selection of reference images in the secondary processing system of the CENS. For the selected initial data, the results of developing an iterative method and algorithm for selecting reference images from the available set based on modeling the brightness distribution of a typical image fragment of the viewing surface under various observation conditions and different resolution capabilities of CENS sensors are presented. The method involves using an iterative procedure for selecting reference images from the multidimensional matrix representation of the set of reference images based on the height parameter determined by the onboard radio electronic equipment of the UAV, and then refining based on angular parameters using the selected rule. An algorithm for implementing the reference image selection procedure based on the proposed method has been developed. However, the authors did not consider the issue of forming a minimal set of the reference images.

Yeromina N. et al. (2021b) proposed methods for synthesizing reference images for the UAV navigation in normal and hyperspectral modes.

Yeromina N. et al. (2018b), Yeromina N. et al. (2020a), Liashko O. et al. (2020), Yeromina N. et al. (2020b), Yeromina N. et al. (2020c), and Vorobiov O. et al. (2020) presented research results on the synthesis of reference images with different levels of informational content and compared them with the current image. Methods for advance and real-time preparation of reference images were proposed based on the use of various invariants. When developing methods for constructing selective images, only the object composition of the viewing surface was considered. This approach made it possible to form reference images based on the most informative objects. It was assumed that the comparison of reference images with the current onboard image would be carried out using the "sliding window" method, and the formation of the comparison result for navigation object location correction would be based on one reference image. This means that these methods have limited applicability, which is a significant disadvantage. The reason for this is that they were not aimed at reducing the computational complexity of image comparison, did not consider the volume of image arrays and the need to form a set of images taking into account possible changes in the perspectives of current image formation on board the UAV.

Literature analysis suggests the prospects of using MR for monitoring ground objects and developing methods for generating reference images to reduce operational volume. At the same time, the problem of reducing computational costs for monitoring critical infrastructure objects using flying mobile robots equipped with a correlation-extreme navigation system remains unresolved. This can be achieved through minimizing the number of fragments of reference images while ensuring the required precision and reliability of monitoring critical infrastructure objects.

METHODS, RESULTS, AND DISCUSSION

To continue the approaches proposed by Tarshin V. A., et al., 2015, and Yeromina N., et al., 2018a for describing current images $\mathbf{S}_{CI}$ of critical infrastructure objects, we will use the brightness values of the corresponding objects and background surfaces in the resolution elements:

$$\mathbf{S}_{CI} = \mathbf{S}_{OI} = \left\| S(i,j) \right\|, \qquad (1)$$

where $\mathbf{S}_{OI}$ is the undistorted source image;

$$S(i,j) = \begin{cases} S_v(i,j), & \text{при } S(i,j) \in \mathbf{S}_v \\ S_w(i,j), & \text{при } S(i,j) \in \mathbf{S}_w \end{cases};$$

$S_v(i,j)-$ is the brightness of the v-th image element of the object $\mathbf{S}_v$;

$S_w(i,j)-$ is the brightness of the w-th image element of the background $\mathbf{S}_w$;

V and W are the number of critical infrastructure objects and backgrounds of different brightness and shapes in the source image, respectively.

We will take into account the following assumptions in the model of the current image:

1) The current and initial images have the same size of $N_1 \times N_2$ pixels;

2) Critical infrastructure objects have significantly higher brightness values compared to the background and are homogeneous in brightness within the resolution element;

3) Each i,j-th element of the current image represents a normally distributed variable with a variance of σ_{ij}^2 and a mean brightness value of $S(i,j)$, which, in the absence of interference, can take one of two values: $S_v(i,j)$ or $S_w(i,j)$;

4) The contrast of critical infrastructure objects relative to the surrounding background is determined as $\Delta S = S_v(i,j) - S_w(i,j)$;

5) The noise variance in the receiving channels of CENS is the same, i.e., $\sigma_{ij}^2 = \sigma^2$, where $i \in \overline{1,N_1}$, $j \in \overline{1,N_2}$;

6) The number of background elements belonging to the set $\mathbf{S}_w$ and critical infrastructure objects belonging to the set $\boldsymbol{S_v}$, satisfies the relation $V << W$.

The probability density functions of the brightness S for the background elements and the critical infrastructure objects, considering the assumptions made, are determined by the following expressions:

$$w_w(S) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\left(S - S_w\right)^2 / 2\sigma^2 \right], \qquad (2)$$

$$w_v(S) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\left(S - S_v\right)^2 / 2\sigma^2 \right]. \qquad (3)$$

Description of a set of reference images.

The wide range of changes in the height of MR $h_i \in [h_{\min}, h_{\max}]$, viewing angles $\alpha_j \in [\alpha_{\min}, \alpha_{\max}]$, $\beta_k \in [\beta_{\min}, \beta_{\max}]$, differences in monitoring direction determined by vector $\mathbf{v}$, as well as temporal changes t_p, necessitates the use of a set of reference images:

$$\begin{gathered}\left\{\mathbf{S}_{RI}(2\theta_{0,5}, h_i, \alpha_j, \beta_k, \nu_l, \varphi_s, t_m)\right\}, \\ i=\overline{1,I},\ j=\overline{1,J}, \\ k=\overline{1,K},\ l=\overline{1,L}, \\ p=\overline{1,P},\ s=\overline{1,S}.\end{gathered} \tag{4}$$

Each individual reference image corresponds to its own matrix of brightness values of the corresponding pixels:

$$\mathbf{S}_{RI} = \left\| S_{RI}(m,l) \right\|,\ m=\overline{1,M},\ l=\overline{1,L},$$

where M, L are the dimensions of the reference images.

Due to the instability both of the absolute brightness values of individual critical infrastructure objects and the contrast between control objects and the background, we will consider that the images are given by the contrast sign and the geometric shape of critical infrastructure objects, i.e. in the form of binary images formed for different heights and viewing angles. The values 1 correspond to the elements of critical infrastructure objects, and 0 to the background elements.

For these models of the current and reference images, we will represent the result of their comparison as follows:

$$\mathbf{R}(\mathbf{r},t) = \mathbf{F}_{SP}\begin{pmatrix}\mathbf{S}_{CI}(\mathbf{r},t), \\ \mathbf{S}_{RI}(2\theta_{0,5}, h_i, \alpha_j, \beta_k, \nu_l, \varphi_s, t_p)\end{pmatrix}, \tag{5}$$

where $\mathbf{F}_{SP}$ is the image comparison operator.

Problem statement.

For the considered image models, based on their comparison, it is necessary to solve the problem of minimizing the number of reference images that form the required set, the use of which will ensure the required accuracy and reliability of monitoring the states of critical infrastructure objects.

Solution.

The set of reference images $\{\bullet\}$ is a multidimensional matrix, the filling of which with individual images, without restrictions on the amount of computation, can be as large as desired, depending on the chosen discretization step, both in height and angles.

Obviously, the smaller the discretization step, the better the correspondence between the selected reference image for comparison and the current image. In other words, the higher the correlation coefficient of the compared images will be.

In addition, the degree of mutual correlation between individual neighboring reference images within the set itself will also be high. Based on this, the solution to the problem can be reduced to establishing the minimum permissible degree of correlation between individual images that make up the set of reference images. At the same time, the accuracy of monitoring the condition of critical infrastructure objects will actually be determined by the steepness of the $\mathbf{R}(\mathbf{r},t)$ function in the region of its maximum, according to the following relationship:

$$\sigma_{\mathbf{R}} = \sqrt{-\frac{1}{\dfrac{\partial^2 \mathbf{R}(\mathbf{r},\mathrm{t})}{\partial \mathbf{r}^2}}}. \tag{6}$$

The reliability of monitoring the condition of critical infrastructure objects will be determined by the unimodality of the $\mathbf{R}(\mathbf{r},t)$, function, or, in other words, through the probability of occurrence of anomalous errors, which can be easily determined using the maximum likelihood method based on expressions (2), (3).

The diversity of critical infrastructure objects, differences in backgrounds, viewing conditions, and the influence of many random factors on the functioning of the MR require the presence of a large amount of statistical data, their generalization, classification, and a non-deterministic approach. Therefore, at this stage of the research, it is advisable to use the method of statistical modeling, since the problem being solved is stochastic. At the first stage of modeling, using various reference images of critical infrastructure objects for possible viewing conditions, it is necessary to construct selective images. The peculiarity of this stage is the obtaining of a set of selective images that will significantly differ in the number of objects in the images for different heights due to the spatial smoothing of objects in the images. This happens because some objects become small and comparable to, or smaller than, the resolution element of the antenna system channel for receiving information as the height increases. Another feature of this stage is the appearance of perspective distortions depending on the orientation of the antenna system (angle of inclination), which also leads to a decrease in correlation by geometric features. At the second stage, it is necessary to compare the reference image with the obtained selective images.

The third stage involves determining the minimum permissible correlation between adjacent reference images forming the required minimum set for the chosen range of viewing parameters, satisfying condition (6) and the unimodality of the function $\mathbf{R}(\mathbf{r},t)$. In the final stage, the minimum number of reference images forming the desired set is determined based on the minimum permissible degree of correlation between individual images.

Modeling will be carried out using images of objects on the viewing surface with different object compositions and for different viewing angles at a height of 500 m. The influence of random factors on the formation of selective images will be considered by selecting the degree of correlation between the initial and selective reference images at a level ranging from 0.5 to 0.7.

Reference images of critical infrastructure monitoring areas, including energy infrastructure, are shown in Figs. 1, 4, 7, 10, 13; binary reference images obtained based on these reference images (Figs. 1, 4, 7, 10, 13) are shown in Figs. 2, 5, 8, 11, 14, and the results of their comparison based on the classical correlation algorithm are shown in Figs. 3, 6, 9, 12, 15.

Fig. 1. Initial image of the monitoring area.

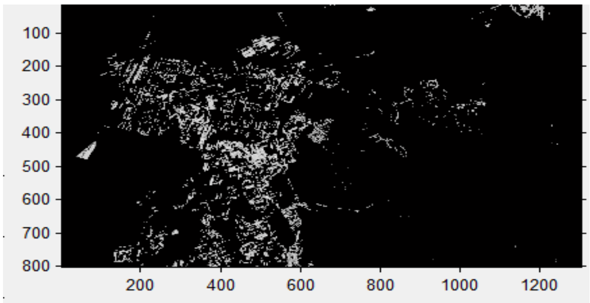

Fig. 2 Binary selective image at the cross-section level over the field of correlation analysis 0.7 to the original image.

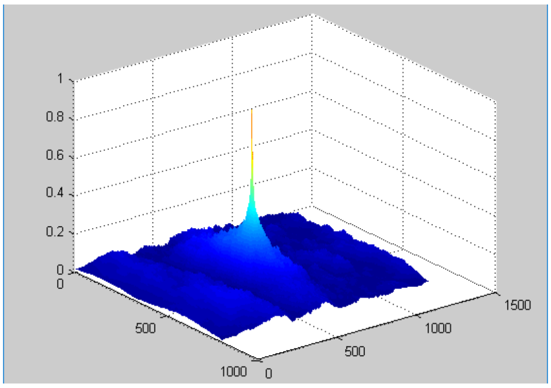

Fig. 3. The result of comparing the original image with its binary selective image.

Let's consider the case when the initial image was obtained at an angle of 30 degrees of viewing.

Fig. 4. The original image of the monitoring area at a viewing angle of 30 degrees.

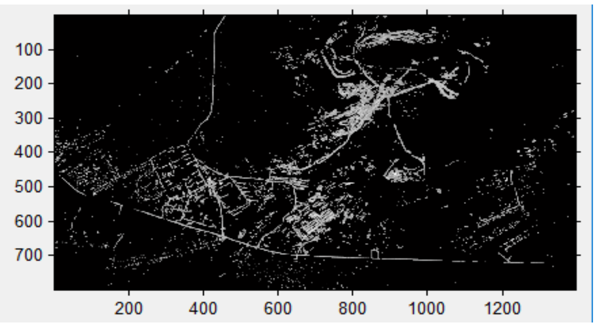

Fig.5. Binary selective image at the cross-section level over the field of correlation analysis 0.6 to the original image.

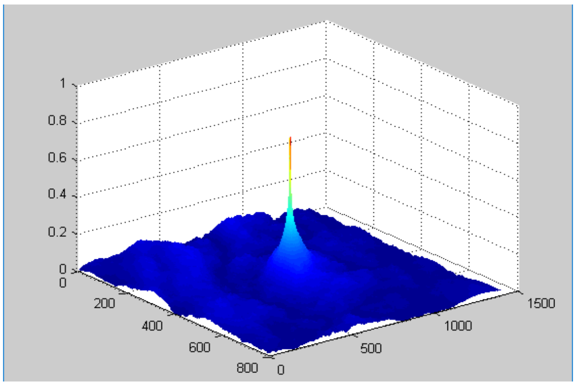

Fig. 6. The result of comparing the original image (Fig. 4) with its binary selective image.

Fig. 7. Initial image of the monitoring area with homogeneous objects of large sizes.

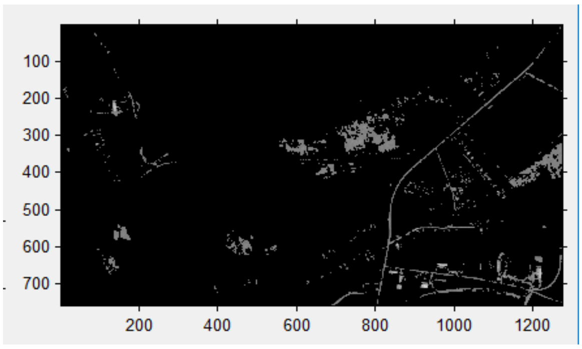

Fig. 8. Binary selective image at a cross-sectional level over the field of correlation analysis of 0.5 to the original image (Fig. 7).

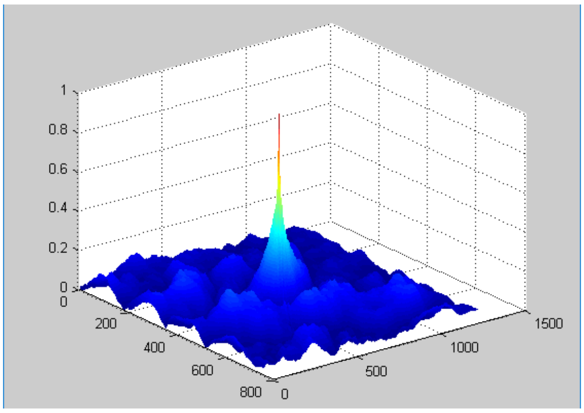

Fig. 9. The result of comparing the original image (Fig. 7) with its binary selective image.

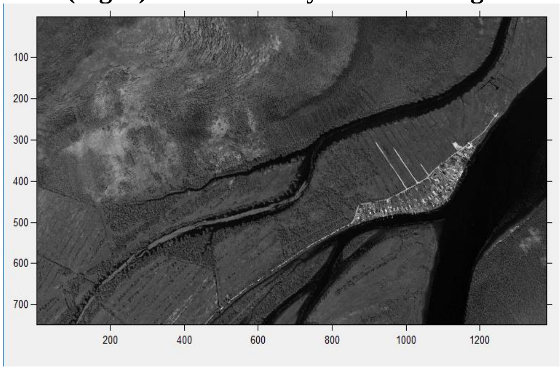

Fig. 10. Original image of a typical landscape.

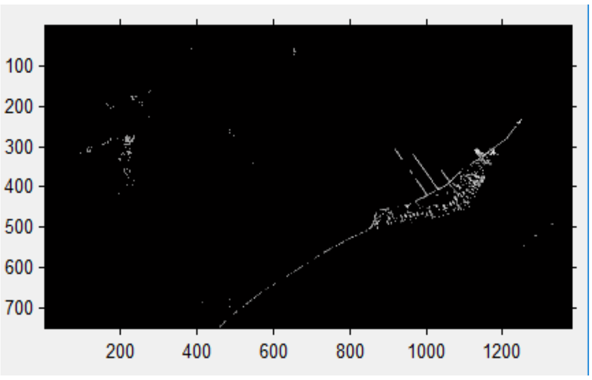

Fig. 11. Binary selective image at a cross-sectional level in the field of correlation analysis of 0.6 to the original image (Fig. 10).

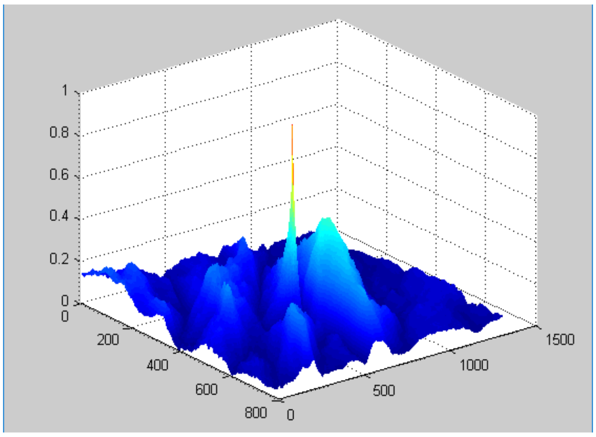

Fig. 12. The result of comparing the original image (Fig. 10) with its binary selective image.

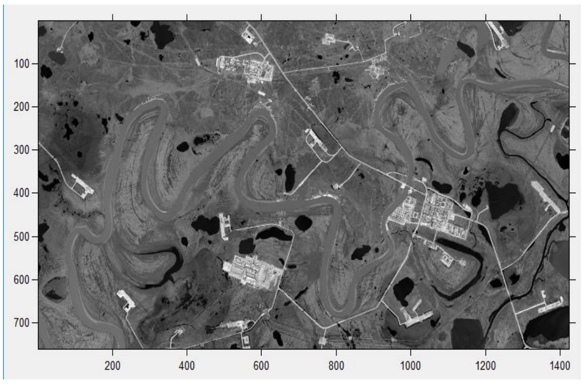

Fig. 13. Original image of a typical landscape with buildings.

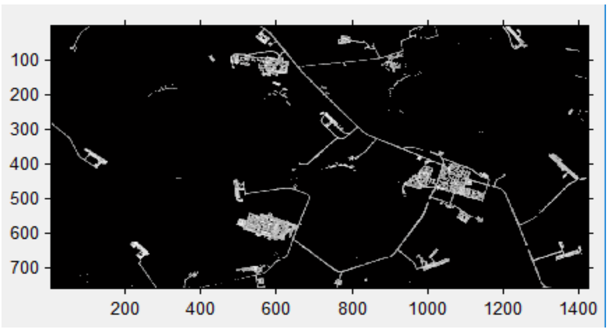

Fig. 14. Binary selective image at a cross-sectional level in the field of correlation analysis of 0.6 to the original image (Fig. 13).

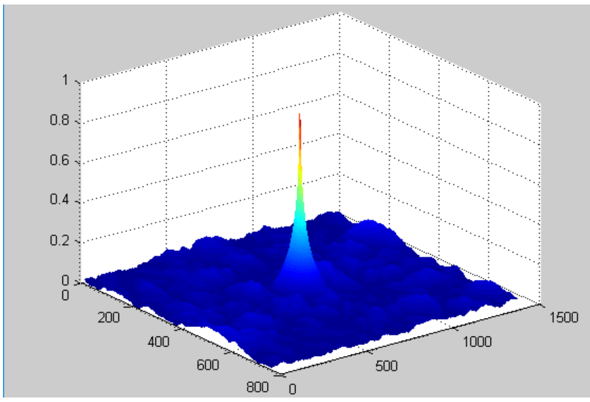

Fig. 15. The result of comparing the original image (Fig. 13) with its binary selective image.

The results of the modeling considering the influence of stochastic factors leading to a decrease in the correlation between images, presented in Figs. 1--15, show that when forming a minimal set of reference images that can ensure the required accuracy and reliability of monitoring the state of infrastructure objects, it is sufficient to maintain a correlation between adjacent images within 0.6. This correlation is ensured with a discretization step for angles within 30 degrees. These modeling results were obtained for a constant value of the height of MR.

The influence of changing in the height of the MR flight on the formation of the image comparison function is shown for the range of heights from 500 to 600 m in Fig. 16.

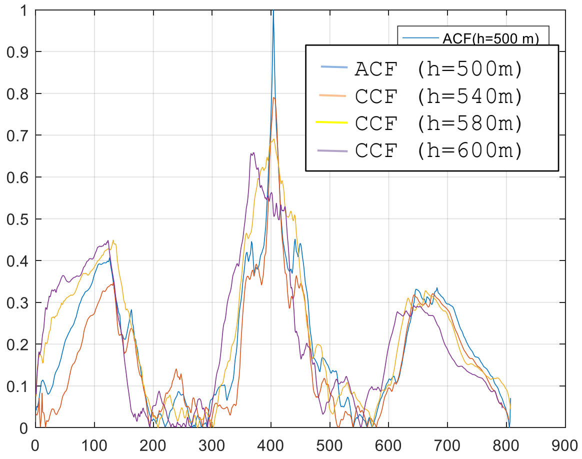

Fig. 16. The results of comparison of the original image with its binary selective image for the height range from 500 to 600 m.

The analysis of the comparison results between the initial image and its binary selective image for the altitude range from 500 to 600 meters, presented in Fig. 16, shows the possibility of using a height discretization step within the range of 80 to 100 meters, which maintains the unimodality of the image comparison function of $\mathbf{R}(\mathbf{r},t)$. At the same time, it is necessary to consider a significant deterioration in the accuracy of image comparison and, consequently, the accuracy of assessing the states of controlled objects.

For example, when the degree of correlation is at the level of 0.5, the accuracy will be in the order of tens of meters, which becomes unacceptable for monitoring the condition of small critical infrastructure objects. In this case, the reliability of monitoring the states of these objects is significantly reduced at a degree of correlation within the range of 0.5, when side outliers appear, comparable in magnitude to the main lobe of the image comparison function.

CONCLUSIONS

As a result of the conducted research, an approach to forming a set of selective images based on correlation analysis of scenes and the sufficient preservation of correlation between neighboring images within 0.6…0.7 has been justified. Such an approach allows for a significant reduction in computational costs by forming a set of reference images with a minimum permissible set of discretization parameters, which are about 30 degrees for angles and 80-100 meters for height. At the same time, high accuracy, and reliability of monitoring the state of critical infrastructure objects are ensured.

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