The Method for Generating a Set of Reference Images for Assessing the Condition of Critical Infrastructure Facilities Using Mobile Robots

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Abstract. The purpose of this work is to improve the accuracy of critical infrastructure condition assessment using mobile robots by considering the geometric distortions of the current images during the formation of a set of reference images. The goal is achieved by determining the sampling step values by angles and sighting height without loss of accuracy. The most important result is the determination of acceptable discretization values in the range of angles and heights of a correlation-extreme navigation system. The significance of the obtained results is in solving the problem of forming a set of reference images, which will reduce the impact of changes in the geometry of sighting on the accuracy of the evaluation of objects. A special feature of the results obtained is the establishment of maximum permissible sampling steps in angles and heights of sight to ensure the required accuracy of object state estimation. When forming a set of reference images, the sampling step by height should be (0.06....0.11)% and (0.12....0.2)% relative to the initial flight altitude for the sighting surface with normal and high object saturation, respectively. The angular sampling step is 10...17 degrees and 6...10 degrees, respectively, for the same surface types. The difference from known works is that the perspective and scale distortions are considered at the stage of formation of a set of reference images, which ensures high accuracy of the system functioning in conditions of orientation and sighting geometry changes.

Keywords: mobile robot, critical infrastructure object, set of reference images, correlation-extremal navigation system, discretization by angles and height.

DOI: https://doi.org/10.52254/1857-0070.2022.3-59.12
UDC: 629.7.052:504.064.36

Metoda de generare a unui set de imagini de referință pentru evaluarea stării instalațiilor de infrastructură critică cu ajutorul roboților mobili

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Rezumat. Scopul acestei lucrări este de a îmbunătăți acuratețea evaluării stării infrastructurilor critice cu ajutorul roboților mobili prin luarea în considerare a distorsiunilor geometrice ale imaginilor curente în timpul formării unui set de imagini de referință. Scopul este atins prin determinarea valorilor pasului de eșantionare în funcție de unghiuri și de înălțimea de vizionare fără pierderi de precizie. Cel mai important rezultat este determinarea valorilor acceptabile de discretizare în domeniul unghiurilor și înălțimilor unui sistem de navigație corelație-extrem. Semnificația rezultatelor obținute constă în rezolvarea problemei de formare a unui set de imagini de referință, care va reduce impactul modificărilor în geometria de vizare asupra acurateței evaluării obiectelor. O particularitate a rezultatelor obținute constă în stabilirea treptelor maxime admisibile de eșantionare a unghiurilor și înălțimilor de vizare pentru a asigura precizia necesară estimării stării obiectelor. La formarea unui set de imagini de referință, pasul de eșantionare pe înălțime trebuie să fie de (0,06....0,11)% și (0,12....0,2)% în raport cu altitudinea inițială de zbor pentru suprafața de vizionare cu saturație normală și, respectiv, ridicată a obiectelor. Pasul de eșantionare unghiulară este de 10...17 grade și, respectiv, 6...10 grade, pentru aceleași tipuri de suprafețe. Diferența față de

lucrările cunoscute constă în faptul că distorsiunile de perspectivă şi de scară sunt luate în considerare în etapa de formare a unui set de imagini de referinţă, ceea ce asigură o precizie ridicată a funcționării sistemului în condiții de schimbare a orientării şi a geometriei de observare.
Cuvinte-cheie: robot mobil, obiect de infrastructură critică, set de imagini de referință, sistem de navigație prin corelație-extremă, discretizare după unghiuri și înălțime

Метод формирования совокупности эталонных изображений для оценки состояний объектов критической инфраструктуры с помощью мобильных роботов

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Аннотация. Целью данной работы является повышение точности оценки состояний объектов критической инфраструктуры с помощью мобильных роботов путем учета геометрических искажений текущих изображений на этапе формирования совокупности эталонных изображений. Поставленная цель достигается путем определения значений шага дискретизации по углам и высоте визирования, с учетом которых необходимо формировать искомую совокупность без потери точности функционирования. Наиболее существенным результатом является определение допустимых значений дискретизации в диапазоне углов и высот функционирования корреляционно-экстремальной системы навигации. Значимость полученных результатов состоит в решении задачи формирования совокупности эталонных изображений, что существенно снизит влияние изменений геометрии визирования на точность оценки состояния объектов, а также уменьшит влияние внешних факторов на полет мобильных роботов, связанных с порывами ветра и «воздушными ямами». Особенность полученных результатов заключается в установлении максимально допустимых значений шага дискретизации по углам и высоте визирования, при которых обеспечиваются требуемая точность оценки состояний объектов критической инфраструктуры. Установлено, что при формировании совокупности эталонных изображений, обеспечивающих требуемую точность, необходимо и достаточно обеспечить значение шага дискретизации по высоте не более (0.06….0.11)% относительно исходной высоты полета для поверхности визирования с нормальной объектовой насыщенностью и (0.12….0.2)% с высокой объектовой насыщенностью. Шаг дискретизации по углам для поверхности визирования с нормальной объектовой насыщенностью необходимо выбирать в пределах от 10 до 17 градусов, а для поверхности визирования с высокой объектовой насыщенностью от 6 до 10 градусов. Отличие от известных работ заключается в учете перспективных и масштабных искажений еще на этапе формирования совокупности эталонных изображений, что существенно упрощает алгоритм вторичной обработки при сравнении изображений, и обеспечивает высокую точность функционирования системы в условиях изменений ориентации и геометрии визирования.
Ключевые слова: мобильный робот, объект критической инфраструктуры, совокупность эталонных изображений, корреляционно-экстремальная система навигации, дискретизация по углам и высоте.

INTRODUCTION

One priority area for assessing the condition of critical infrastructure objects, overhead power transmission lines above land and sea, and conducting search and rescue operations in water areas is the further development and use of flying mobile robots (MRs). They allow obtaining a necessary information on the observed objects regardless of the complexity of access to them, including daily, weather conditions, and seasonal variations. High-precision correlation-extremal navigation systems (CENS) are installed on board modern mobile robots, which simultaneously serve as the information extraction systems about the observed objects.

The efficiency of using such an MR is determined by numerous internal and external factors. Among these factors, with random characteristics, geometric conditions of sighting and orientation of the mobile robots hold a significant position. These conditions can lead to discrepancies between the images formed during monitoring, referred to as Current Images (CI), and the pre-prepared Reference Images (RI). This is due to the complexity of ensuring identical conditions to obtain the original information necessary both forming RI and CI. As a result, discrepancies arise due to perspective and scale distortions, which need to be considered during the secondary image processing stage for the image comparison. This circumstance inevitably necessitates the real-time elimination of such distortions, which complicates the procedure of forming the comparison result and, consequently, reduces the efficiency in the secondary processing of CENS. Moreover, the accuracy of CENS functioning is also decreased.

One possible way to solve this issue in assessing the condition of critical infrastructure objects, aerial power lines, and conducting search and rescue operations is to consider the potential perspective and scale distortions starting even from the stage of forming a set of reference images. This can be achieved by constructing a set of reference images for values of the discretization step in angles and elevation, at which the minimum permissible correlation link will be provided between the neighboring image fragments that form the initial set based on the selected informative indicator. Such an approach will ensure high accuracy indicators of CENS, and any discrepancies between the compared images will be limited to the discretization range in angles and elevation.

Thus, based on the requirements for ensuring accuracy, it is possible to determine the values of the discretization step within the ranges of elevation and viewing angles. Additionally, this approach will provide the necessary set of reference images with the minimum number of images without compromising accuracy and with the highest speed. As a result of implementing this approach, a reliable assessment of the condition of critical infrastructure objects and aerial power lines, as well as the search and rescue operations, etc., will be ensured.

To date, a significant number of publications have been dedicated to the development of methods and algorithms to enhance the efficiency of mobile robot operation. However, little attention has been paid to the formation of a set of reference images, the use of which leads to a significant reduction or complete elimination of the influence of perspective and scale distortions. Therefore, this article proposes a method for forming a set of reference images used in mobile robots for assessing the condition of critical infrastructure objects, aerial power lines over land and sea, and conducting search and rescue operations in water bodies, with consideration for reducing or eliminating the influence of scale and perspective distortions.

Let us examine the known methods and results for solving the problem of enhancing the efficiency of CENS and forming reference images for them.

PUBLISHED LITERATURE ANALYSIS

Chakraborty, P. et al. (2022) presented the results of detecting duplication forgery regions using the COMOFORD database, employing Discrete Cosine Transform (DCT), k-dimensional tree (kd-tree) for efficient sorting, and a reliable matching method. By using a 16×16 block size divided into four parts, forgery can be detected in PNG images with higher performance, identifying images with a quality factor of 0.5 and a threshold value of 10. Good results were also obtained for JPEG images.

Rohini A Maind et al. (2014) presented a method that allows comparing Discrete Cosine Transform (DCT) and Principal Component Analysis (PCA) for detecting the image forgery.

Tymochko O. et al. (2020) presented the results of synthesizing optimal Reference Images. The synthesis is based on the concept of scale from the theory of measurements. The brightness component of RI, as well as shifts and rotations of RI with respect to CI, and the operation of enumerating CI fragments with the sizes of RI, have been proposed to be formalized in terms of Grenander's pattern theory.

Tarshin V. A. et al. (2015) proposed a method for operational formation of a RI using fractal analysis. The issues of forming a set of images were not considered.

Sotnikov A. et al. (2017) offered a solution to the problem of object localization against false interference. The influence of geometric distortions was not taken into account.

Pakhomov A.A. et al. (2015) investigated the influence of the atmosphere on the formed image. A software suite was developed to eliminate various types of atmospheric distortions and dark nighttime background in order to improve the image clarity.

Fernandes, L. et al. (2008) considered approaches to object contour detection and localization on images using the Hough transformation.

Fursov, V. A. et al. (2013) investigated the influence of scale distortions on object localization. In this case, a single Reference Image was used.

S. Maji & J. Malik (2009) presented results of optimal object detection on images.

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

Trefilov P.M. (2019) demonstrated the feasibility of using Strapdown Inertial Navigation Systems (SINS) in the composition of Unmanned Aerial Vehicles (UAVs). Both physical and algorithmic methods for improving SINS were examined. It was shown that the physical method allows reducing the rate of error accumulation but cannot eliminate them. The application of algorithmic methods based on integration with other measurement systems allows reducing SINS errors.

Scaramuzza D., et al. (2014) presented experimental results demonstrating the autonomous navigation of three Micro Aerial Vehicles (MAVs) in an unknown environment without GPS but using three-dimensional mapping and optimal coverage. The limitation of the study is the lack of information on the potential use of this approach for the object state estimation and reference image formation.

P. Sabeena Burvin & J. Monica Esther (2014) showed that retouching minimally alters images. It merely enhances some features of the image. Subtypes of digital image retouching were considered, mainly technical retouching and creative retouching.

Kostyashkin L. N. et al. (2014) examine approaches to developing a combined vision system for aviation. The merit of the work lies in the development of algorithmic methods to reduce the complexity of image fusion based on geometric alignment, necessary with cartographic and navigational errors, and visualize geometrically aligned images considering flight conditions and visibility. However, a drawback of the study is the inability to use the developed methods without pilot involvement.

Loginov A.A. et al. (2015) investigated the reduction of computational complexity in fusing heterogeneous images in an aircraft's combined vision system.

Elesina S. & Lomteva O. (2018) present the results of the research on the genetic algorithm aimed at obtaining optimal settings when used in combined vision systems. The feasibility of using the extended angles of reference images in the search for global extrema is demonstrated. It is shown that using such an approach increases the system's performance by 5 times. However, the authors did not consider the influence of possible perspectives of reference and current images on real-time feasibility.

Sotnikov O et al. (2020) examined the methods to ensure the accuracy of MR navigation and considered the influence of stochastic factors on the formation of current images. However, the work does not consider the issues of forming a set of the reference images.

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

Vorobiov O. et al. (2020) suggested the approaches for extracting information under conditions of changing propagation path status and prior uncertainty of informative parameters of objects on the viewing surfaces (VS).

D. Vaishnavi & T.S. Subashini (2019) propose a novel approach for forgery detection through copy-move manipulation using local symmetry-based features. The proposed scheme is also capable of detecting multiple copies of forgeries and localizing the identified regions.

Meena K.B. & Tyagi V. (2019) propose a novel method for detecting image forgery through copy-move manipulation using Gauss-Hermite moments (GHM). Experimental results demonstrate that the proposed method accurately localizes the regions of copy-move manipulation in the manipulated image.

Salah, A. et al. (2020) disclose the problems of parallelizing quaternion moment computations and propose a method for processing color images.

Hamza, H. M. et al. (2023) present a new system for detecting the image forgery with parallel copy-move and manipulation (PCMIFD) using multi-core processors.

The analysis of the literature indicates the prospects of using MR for monitoring ground objects and developing methods for generating reference images to reduce the volume of operations. However, reduction of computational costs remains unresolved issue when monitoring the states of critical infrastructure objects using flying mobile robots equipped with correlation-extreme navigation systems. This reduction is based on minimizing the number of fragments of reference images that can achieve the set goal while ensuring the required accuracy and reliability of monitoring critical infrastructure objects.

METHODS, RESULTS, AND DISCUSSION

The decision function (DF), as a result of comparing the current and reference images, is generally described by the following expression:

$$\mathbf{R}(\mathbf{r},t,\theta,\theta_i)=\mathbf{F}_{SP}\left(\mathbf{S}_{CI}(\mathbf{r},t,\theta),\ \mathbf{S}_{RI}(\theta_i)\right), \quad (1)$$

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

$\mathbf{S}_{CI}(\mathbf{r},t,\theta)$ is the current image;

$\mathbf{S}_{RI}(\theta_i)$ is the reference image.

According to the approaches adopted by Chakraborty et al. (2022), Rohini A Maind et al. (2014), Tarshin V. A. et al. (2015), Vorobiov O. et al. (2020), and D. Vaishnavi and T.S. Subashini (2019), the current images $\mathbf{S}_{CI}$ are described by the brightness values of objects and background on the visualized surface elements:

$$\mathbf{S}_{CI} = \left\| S\left(i,j\right) \right\|, \qquad (2)$$

where

$$S\left(i,j\right) = \begin{cases} S_v\left(i,j\right), & \text{if } S\left(i,j\right) \in \mathbf{S}_v \\ S_w\left(i,j\right), & \text{if } S\left(i,j\right) \in \mathbf{S}_w \end{cases} \qquad (3)$$

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

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

V and W are the number of critical infrastructure objects and backgrounds with different brightness and shapes in the original image.

The reference image is also described as a matrix of brightness values for 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 image.

Problem statement.

For the current image $\mathbf{S}_{CI}(h_i, \alpha_j, \beta_k, \nu_l, \varphi_s)$ formed at a certain moment in time t_m within the range of possible changes in the mobile robot's flight height $h_i \in [h_{\min}, h_{\max}]$, viewing angles $\alpha_j \in \left[\alpha_{\min}, \alpha_{\max}\right]$, $\beta_k \in \left[\beta_{\min}, \beta_{\max}\right]$, and orientation $\mathbf{v}$, it is hypothetically necessary to create a set of reference images $\{\bullet\}$, whose use during the determination of $\mathbf{R}(\mathbf{r},t)$ will minimize the influence of geometric distortions and achieve the best accuracy in assessing the state of critical infrastructure objects: $\Delta\mathbf{R}(\mathbf{r},t) \to \min$.

In other words, it is necessary to find discretization parameters in height Δh, viewing angles $\Delta\alpha, \Delta\beta$, and orientation $\Delta\mathbf{v}$, that, when used during the formation of the set of reference images $\{\bullet\}$, will subsequently ensure that when selecting one of the reference image fragments, $\Delta\mathbf{R}(\mathbf{r},t) \to \min$.

Solution of the problem.

Let's examine the influence of geometric distortions on the formed CENS CI. For this purpose, we will use geometric constructions. The influence of scale distortions is shown in Fig. 1, and the influence of perspective distortions is shown in Fig. 2.

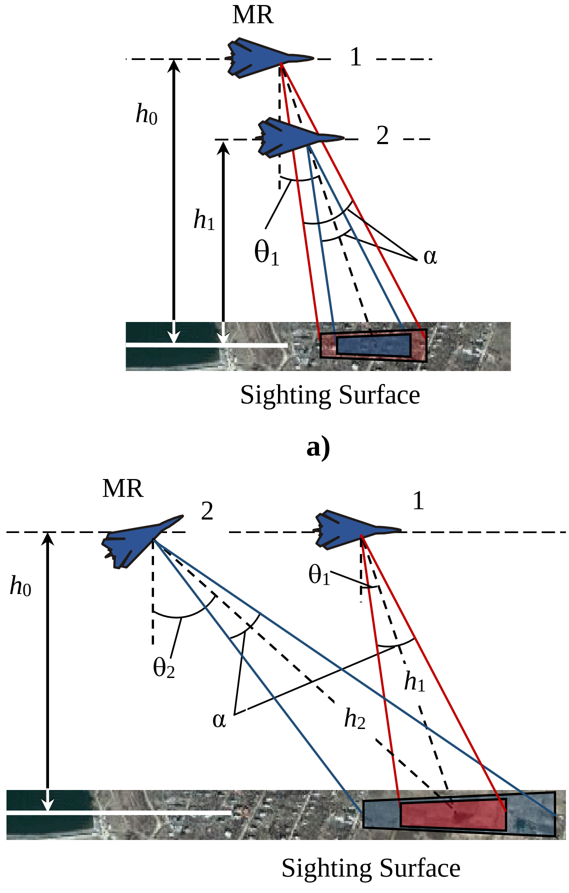

Fig. 1. Sighting geometry in the presence of: a) scale; b) perspective distortion

Changes in the altitude of the MR (as seen in Fig. 1a)) result in linear changes in the image dimensions, while changes in the viewing angles of the CENS (Fig. 1b)) lead to trapezoidal (non-linear) changes in the CI dimensions ($m_1 \times n_1, m_1 \times n_2$).

Scale distortions of the CI relative to the original size ($m_1 \times n_1$) of the image can be described by the following expressions:

$$m_1 = mh_0(1 + \frac{\Delta h}{h_0}), \qquad (4)$$

$$n_1 = nh_0(1 + \frac{\Delta h}{h_0}), \qquad (5)$$

where $\Delta h = h_0 - h_1$ is the change in the altitude of the MR.

Changes in the viewing angles also cause distortions in the CI dimensions, which can be determined according to the following expressions:

$$m_1 = m\frac{\cos(\theta_1 + \Delta\theta)}{\cos(\theta_1)}, \qquad (6)$$

$$n_1 = n\frac{\cos(\theta_1 - \alpha/2)}{\cos(\theta_1 + \Delta\theta - \alpha/2)}, \qquad (7)$$

$$n_2 = n\frac{\cos(\theta_1 + \alpha/2)}{\cos(\theta_1 + \Delta\theta + \alpha/2)}, \qquad (8)$$

where $\Delta\theta = \theta_2 - \theta_1$ is the change in the orientation angle of the MR.

Unlike the scale distortions, perspective distortions do not only lead to changes in slant height but also affect the relative dimensions of the CI. This is an important aspect that must be considered when selecting RI from the set, as ambiguity may arise due to high correlation between images for other geometric viewing conditions.

Thus, taking into account the geometric distortions, the decision function (DF) can be represented in the general form by the expression:

$$R(\Delta h, \Delta\alpha, \Delta\theta) = \\ = F_{SR}\begin{pmatrix} S_{RI}(m_1, n_1), \\ S_{CI}\left(m_2(\Delta h, \Delta\alpha, \Delta\theta), n_2(\Delta h, \Delta\alpha, \Delta\theta)\right) \end{pmatrix}. \qquad (9)$$

Expression (9) implies that the smaller the discretization step, the higher the degree of mutual correlation between RI and CI. Let's assess the impact of geometric distortions on the correlation degree of the compared images. For this purpose, we use the results of statistical modeling performed using the classical correlation algorithm for typical viewing surfaces with normal F_1 ($V_{min} < V \le V_{max} = 10...15$) and high object density F_2 ($V > V_{max}$).

During modeling, it was assumed that the size of the RI is 100×100 pixels. The sizes of the CI correspond to the selected shooting mode with normal and high object density, which are 1280×720 pixels.

The flight height of the MR was chosen from 500 to 600 meters. Both the brightness of the objects themselves and the contrast between them were used as informative parameters to describe the objects in the image.

The results of modeling the influence of scale distortions on the coefficient of mutual correlation (CMC) of the compared images are presented in Fig. 2, while the results for perspective distortions are shown in Fig. 3.

When determining the dependence of the CMC on changes in the viewing angle, it was assumed that $\alpha = 40^\circ$.

The analysis of the results presented in Fig. 2 and Fig. 3 of the modeling shows that the formation of the unimodal DF that ensures high accuracy in estimating the states of critical infrastructure (SCI) ($K(\Delta h) = 0.8...0.9$) is possible with a discretization step in height within the range of 0.06….0.11 relative to the original flight height for viewing surfaces (VS) with normal object density. For VS with high object density, this parameter can be in the range of 1.12….1.2. The discretization step in angles for VS with normal object density should be selected within the range from 10 to 17 degrees, and for VS with high object density – within 6 to 10 degrees. The feasibility and possibility of using a larger discretization step in height and viewing angles for highly object-dense viewing surfaces are justified due to the inevitable appearance of false objects in the images when the viewing conditions change.

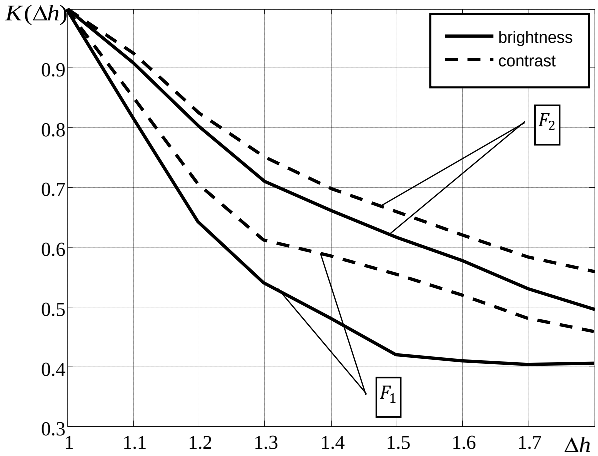

Fig.2. Dependence of CCC on changes in the height of TI formation.

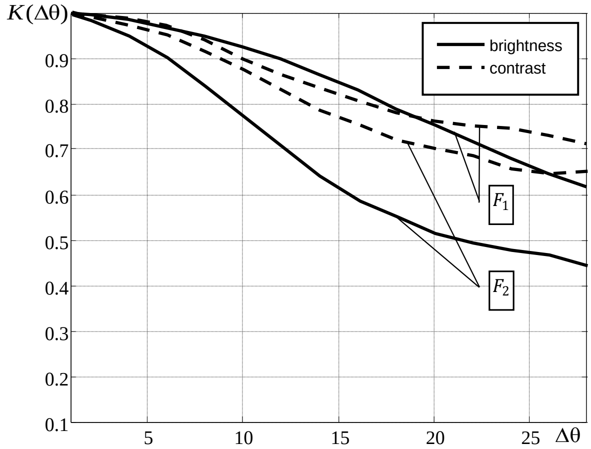

Fig. 3. Dependence of CCC on changes in viewing angle.

As mentioned above, let's consider that perspective distortions, unlike scale distortions, lead not only to changes in the slant height but also to changes in the relative sizes of CI.

In other words, it is possible to reduce the number of RI fragments in the sought set since the correlation degree for certain changes in angles and heights can be the same. This condition can be expressed as follows:

$$K(\Delta h) = K(\Delta\theta)\,. \qquad (10)$$

Satisfying condition (10) allows reducing the number of RI fragments in the set and decreases the computational burden during the formation of the DF. However, it leads to ambiguity in selecting the RI fragment from the set. Elimination of this ambiguity occurs during the secondary processing stage.

CONCLUSIONS

As a result of the conducted research, a method for forming a set of reference images (RI) has been developed. The method is based on determining the values of the discretization step in angles and height of the CENS (correlation-extremal navigation system), which allows considering the influence of geometric distortions on the system's performance during the formation of the RI set. Such an approach significantly simplifies the algorithm of the secondary processing of the system and ensures high accuracy of its functioning under changes in the viewing geometry. Moreover, the computational costs are substantially reduced by forming the minimum permissible number of reference images in the set based on the discretization parameters in angles and height.

During further research, a series of experiments are planned to collect statistical data and expand the database to achieve the best accuracy in evaluating the state of critical infrastructure objects.

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