Estimation of the aircraft's position based on optical channel data

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Abstract
Paper presents a mathematical support for solving the problem of navigation along the optical channel of an aircraft. The stages were formalized and the main notations were introduced, a formal procedure for obtaining coordinates of special points of a digital image from aircraft cameras was presented. It is proposed to determine the coordinates of the aircraft based on the method that uses the estimation of the density function of the distribution of the coordinates of special points of the digital image. A method of verifying the reliability of the aircraft position assessment based on consistency measures has been formulated. The results of testing the proposed algorithm are given. Conclusions are formulated.

Keywords
autonomous flight control UAV navigation, optical channel data, aircraft position, estimation image processing, GPS-denied environment, optical sensors

1. Introduction

The relevance of this topic is determined by the increasing significance of unmanned aerial vehicles (UAVs) for various applications, including surveillance, reconnaissance, monitoring, and data collection. With the advancement of UAV technologies, the importance of accurate and reliable methods for assessing the vehicle's location becomes critical to ensure the effectiveness and safety of their operations [1]. Precise assessment of UAV location is crucial for the successful execution of missions, navigation, and control. This is especially important in scenarios where optical channels, such as cameras or sensors, play a key role in determining the aircraft's location. Location assessment methods based on optical channels are valuable for applications such as aerial imaging, search and rescue operations, environmental monitoring, and precision agriculture. Furthermore, the ability to assess the location of the UAV based on optical data is significant in urban environments, where GPS signals may be delayed or less reliable [2, 3]. Optical channels provide an alternative means of obtaining spatial information and enhancing UAV autonomy. Research in this field addresses challenges related to the development of reliable algorithms, image processing methods, and mathematical models that can accurately assess the UAV's location using optical data. The topic is relevant special points only for the advancement of UAV capabilities but also for addressing safety issues, regulatory requirements, and the integration of UAVs into various industries. Overall, assessing the location of unmanned aerial vehicles based on optical channels is a pertinent and evolving research area with broad practical implications.

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2. Review of existing solutions and literature sources

Today, navigation systems for aircraft are the object of many studies. Both scientific institutions and commercial business organizations around the world are actively engaged in this issue. Special attention is paid to aircraft navigation in the absence of GPS signals [4].

This paper [5] presents a multi-tier UAV localization module that leverages GNSS, inertial, and visual-depth data. The module is designed to enhance the localization accuracy and reliability of UAVs in challenging environments.

The study proposes a novel integration scheme combining GNSS, INS, and LiDAR data for UAV-based navigation, particularly in areas where GNSS signals are obstructed or unreliable [6]. The integration aims to ensure continuous and accurate navigation. This research [7] introduces a low-cost solution for UAV navigation in GPS-denied environments. The solution focuses on the use of alternative sensors and methods to maintain accurate positioning and navigation without GPS signals. The article [8] discusses a multilevel architecture for autonomous UAVs, aiming to improve their operational capabilities and autonomy. The architecture addresses various challenges in UAV operation, including decision-making and environmental interaction.

It is proposed to compensate for the work of satellite navigation due to the introduction of additional optical navigation sensors. Sensors are integrated using the Kalman filter and its modifications, for example [9, 10].

Much attention is paid to the application of AI in navigation systems. In work [11] for visual odometry, in work [12] for optimization of sensor data integration. The method of determining the presence of GPS navigation obstacles is described in [13].

This research [11] focuses on a deep learning-based LSTM model to enhance visual odometry navigation systems. The model aims to increase the accuracy and robustness of UAV navigation using advanced machine learning techniques.

The article [12] discusses adaptive step size learning with applications to velocity-aided inertial navigation systems. The approach aims to optimize the performance of inertial navigation systems through adaptive learning techniques.

This study [13] introduces a deep-ensemble-learning-based GPS spoofing detection method for cellular-connected UAVs. The method aims to enhance the security and reliability of UAV navigation by detecting and mitigating GPS spoofing attacks.

The works of Ukrainian authors [14–18] and author's additions [2, 19–25] are worthy of attention.

3. The method of determining the position of the aircraft

3.1. Preliminary indications and assumptions

It is assumed that the flight mission can be performed in the area where relevant data has been previously collected. This requirement is put forward due to the fact that a set of descriptors of special landmark points, together with their associated coordinates, must be stored on board the UAV during the flight. So, the first step should be to conduct aerial photography and link the images to the digital map.

Linking pictures to a digital map is a separate task [1], in the further explanation we will assume that a similar operation is performed, i.e., for each pixel of digital picture coordinates are matched.

The second stage is the direct selection of special points and the determination of their descriptors, it is described in detail in [2, 19, 20]. Given the potentially large number of features (landmarks) in the aerial survey data, special attention should be paid to reducing their number by reducing the original image with smoothing.

Thus, pre-flight preparation should ensure the availability of a text (or special format) file with descriptors of special points and their corresponding coordinates on the on-board computer during the flight mission

$$Orient = \{(m_l(i,j), \theta_l(i,j); i = \overline{-3,3}, j = \overline{-3,3}), (x_l, y_l); l = \overline{1,N}\},$$

where $m_l(i,j)$ is magnitude; $\theta_l(i,j)$ is angle; N is the number of special points.

The third stage is a flight mission. If it is necessary to position the aircraft, the on-board computer processes received picture from the target camera in order to find features and compare their descriptors with the available descriptors of the Orient array. The purpose of the comparison is to form a new array containing a list of coordinates corresponding to the matching descriptors:

$$Poz = \{(x_k, y_k); k = \overline{1, M}\},$$

where M is the number of singular points in the image, or the actual number of descriptor matches, if some distance metric threshold is introduced.

In the following, we will analyze the set of coordinates of the array Poz as a sample of realizations of some random variable. The purpose of such an analysis is to establish the most likely location of the aircraft, depending on the probability distribution of Poz data.

3.2. Selection of special points for positioning the aircraft

Let's consider the approach to the selection of special points on the digital image from the camera of the target load of the UAV directly during the flight mission. After detecting singular points using the operators discussed in [2, 19, 20], the task of finding singular points that are common to the reference and test images arises.

Let be

$$Orient = \{(m_l(i,j), \theta_l(i,j); i = \overline{-3,3}, j = \overline{-3,3}), (x_l, y_l); l = \overline{1, N}\}$$

– a set of descriptors of control singular points with their corresponding coordinates,

$$B = \{(m_k(i,j), \theta_k(i,j); i = \overline{-3,3}, j = \overline{-3,3}), (i\_pos_k, j\_pos_k), k = \overline{1, M}\}$$

– a set of descriptors of special points of the test image and corresponding pixel indices of the digital image,

$$i\_pos_k \in [0; Heigth - 1]; \quad j\_pos_k \in [0; Width - 1],$$

where $Heigth$, $Width$ - height and width of the picture from the LA camera.

If the values of the magnitude m_l and angles θ_l are normalized, then as a measure of the distance between the descriptors can be used a metric based on the Euclidean distance

$$d_{lk} = \sqrt{d_{lk}^m + d_{lk}^\theta},$$

where

$$d_{lk}^m = \sum_{i=-3}^{3} \sum_{j=-3}^{3} \left(m_l(i,j) - m_k(i,j)\right)^2; \; d_{lk}^\theta = \sum_{i=-3}^{3} \sum_{j=-3}^{3} \left(\theta_l(i,j) - \theta_k(i,j)\right)^2;$$

$$l = \overline{1, N}, \; k = \overline{1, M},$$

For each k-point of the test picture the nearest l-point of the array $Orient$ can be found from the condition:

$$d_k^{minmin_l\{d_{lk}\}}, \tag{1}$$

thereby defining a two-dimensional array of coordinates $Poz = \{(x_k, y_k); k = \overline{1, M}\}$, corresponding to the positions of special points $\{(i\_pos_k, j\_pos_k), k = \overline{1, M}\}$ on the current digital picture from UAV cameras. Therefore, an array can be entered into consideration

$$Poz_{Index} = \{(i_{pos_k}, j_{pos_k}, x_k, y_k); k = \overline{1, M}\}, \tag{2}$$

in which the indices of special points on the digital terrain image are matched with some coordinates from the array $Orient$.

3.3. Preliminary determination of the coordinates of the aircraft

Let the Poz_Index coordinate array be obtained as a result of comparing the descriptors of special points on the picture and the data of the $Orient$ array. It is necessary to determine the point $Poz\_Plane(x, y)$, which contains the most likely coordinates near which the aircraft is located.

There is always a possibility that the obtained points (2), which are assigned the coordinates of the Poz array, may belong to the image of the landmark object in the test image, and may just coincidentally be similar to such special points. If the two-dimensional density distribution [2] of the coordinates of the Poz array is estimated non-parametrically, then their compact arrangement will determine the coordinates of a separate sought landmark, if it is represented by a compact set of detector points. In words, we are talking about searching for areas on the XY plane where such a density estimate will have local maximum, or one global maximum if there is only one landmark in the field of vision of the aircraft's target load cameras.

As an estimate of the two-dimensional distribution density by the Poz array, we can choose construction and analysis of a histogram of relative frequencies to localize rectangular areas of the probable location of landmarks, and already within the specified areas, we can determine a typical value among x_l and y, $l = \overline{1, M}$. For example, taking about the central point of the corresponding rectangle.

To construct a two-dimensional histogram of the relative frequencies of the coordinate distribution, the following is proposed. Let some (in general, arbitrary) h_x>0, h_y>0.

Let's set the division Δ_{h_x,h_y} of the area of implementation of coordinates x_l, y_l, $l = \overline{1, M}$, the upper left corners of which are determined by points with indices Δ_{h_t,h_q}: $(xxy_{min_{min}})$, $ii = \overline{0, Nn-1}$, $jj = \overline{0, Mm-1}$, where Nn, Mm - the number of areas in the respective directions

$$x \underset{l=\overline{1,M}}{min}\{x_l\}_{min},$$

$$y \underset{l=\overline{1,M}}{min}\{y_l\}_{min}.$$

The relative frequencies of the distribution, which determine the empirical probability of the appearance of a special point from the Poz array in a specific local partition area Δ_{h_x,h_y}, are obtained as follows:

$$f_{ii,jj} = \frac{1}{N} \sum_{k=1}^{N} I_k, \quad ii = \overline{0, Nn-1}, jj = \overline{0, Mm-1},$$

where

$$I_k = \begin{cases} 1, \ if \ ii = \left[\frac{x_l - x_{min}}{h_x}\right] \ and \ \left[\frac{y_l - y_{min}}{h_y}\right], \\ \qquad 0, otherwise. \end{cases}$$

Some (ii, jj)-and the area of division Δ_{h_t,h_q}, where the condition is true $\underset{ii,jj}{max}\{f_{ii,jj}\}$ and will contain the geometric location of the landmark object, and the central point of (ii, jj) area can be taken as the position of the aircraft

$$Poz\_Plane(x, y): \left\{x = x(ii + 0{,}5)_x(jj + 0{,}5)_{y_{min_{min}}}\right\}.$$

If we assume that the search object on the test image can be located within several areas, then for their localization it is enough to select the areas where the condition is fulfilled

$$f_{ii,jj} \geq f_{threshold}, \tag{3}$$

where $f_{threshold}$ is some threshold value.

Then the position of the aircraft can be chosen as the weighted average of the coordinates of the centers of the rectangles, where the condition (3) is fulfilled, i.e.:

$$Poz\_Plane(x, y): \{x = \bar{x}; y = \bar{y}\},$$

where

$$\bar{x} = \sum_{ii=0}^{Nn-1} \sum_{jj=0}^{Mm-1} x_{ij} \cdot \frac{f_{ij} \cdot J_{ij}}{\sum_{ii=0}^{Nn-1} \sum_{jj=0}^{Mm-1} f_{ij} \cdot J_{ij}}; \qquad \bar{y} = \sum_{ii=0}^{Nn-1} \sum_{jj=0}^{Mm-1} y_{ij} \cdot \frac{f_{ij} \cdot J_{ij}}{\sum_{ii=0}^{Nn-1} \sum_{jj=0}^{Mm-1} f_{ij} \cdot J_{ij}}; \tag{4}$$

$$J_{ij} = \begin{cases} 1, & f_{ii,jj} \geq f_{treshold}, \\ 0, & f_{ii,jj} < f_{treshold}. \end{cases}$$

Values $f_{ii,jj}$, $ii = \overline{0, Nn-1}$, $jj = \overline{0, Mm-1}$ provide the empirical probability of the appearance of landmark detectors in areas of division Δ_{h_x,h_y}, so, if one such region is chosen (the most likely), then the probability P that the found region contains the object is:

$$P = \underset{ii,jj}{max}\{f_{ii,jj}\},$$

and if the object occupies several areas, then:

$$P = \sum_{ii=0}^{Nn-1} \sum_{jj=0}^{Mm-1} f_{ii,jj} \cdot J_{ii,jj}.$$

That in the last case, the estimation of the location of the aircraft based on weighted averages (4) is robust, because improbable coordinates are simply taken into account.

3.4. Verification of the reliability of the determined position of the aircraft

We formalize the criterion for verifying that the received coordinates of the features of the current picture really correspond in most cases to the area where the aircraft is located.

For example, if a complete inconsistency is observed for the components of the array (2), then this is evidence that the determined coordinates of the features (x_k, y_k) do change ordinarily due to the change in the positions$(i_pos_k, j_pos_k) k = \overline{1, M}$ of special points in the picture.

As an estimate of the degree of consistency, it is possible to propose the use of Spearman or Kendall rank correlation coefficients between array vectors:

$$\begin{gathered} \{(x_k, i\_pos_k); k = \overline{1, M}\}, \{(y_k, i\_pos_k); k = \overline{1, M}\}, \\ \{(x_k, j\_pos_k); k = \overline{1, M}\} \text{ та } \{(y_k, j\_pos_k); k = \overline{1, M}\}. \end{gathered} \quad (5)$$

Let the corresponding rank array be obtained for any of the specified arrays $\{(r_{I,k}, r_{J,k}); k = \overline{1, M}\}$, where $r_{I,k}$, $r_{J,k}$ – ranks, i.e. serial numbers of the variant in variation series by x_k or y_k $k = \overline{1, M}$ and i_pos_k or $j\_pos_k k = \overline{1, M}$; index $I = \{x, y\}$; index $J = \{i\_pos, j\_pos\}$.

The value of Spearman's rank correlation coefficient $\hat{\tau}_c$ is calculated according to the formula

$$\hat{\tau}_c = 1 - \frac{6}{M(M^2-1)} \sum_{k=1}^{M} d_k^2, \text{ де } d_k = r_{I,k} - r_{J,k}.$$

Significance $\hat{\tau}_c$ is determined on the basis of a hypothesis $H_0: \tau_c = 0$, for the verification of which a statistical characteristic is

$$t = \frac{\hat{\tau}_c \sqrt{M-2}}{\sqrt{1-\hat{\tau}_c^2}},$$

it has t -distribution with the number of degrees of freedom $\nu = M - 2$.

And if

$$|t| \leq t_{1-\frac{\alpha}{2}, \nu}, \quad (6)$$

$t_{1-\frac{\alpha}{2}, \nu}$ - quantile of the t-distribution; α - the probability of an error of the first kind when accepting a hypothesis H_0 (level of significance), when here is no consistency between the determined coordinates of special points and their location on the digital image, and the obtained coordinates of the location of the UAV should raise doubts.

If (6) is true for each of arrays (5), when the position of the aircraft $Poz\_Plane(x, y)$ can be considered statistically justified.

For a more reliable assessment of the consistency of the coordinates of the selected features with their positions on the digital image, it is advisable to check the corresponding hypotheses for all data arrays (5), but only for those that fall into the partition areas for which condition (3) is fulfilled. In this case, it should be expected that random "coincidences" of descriptors will be characteristic of points that are in areas with a relatively low level of relative frequencies. In further research, it is worth paying attention to the possibility of evaluating the consistency of elements of arrays (5) separately for each of the elementary areas of division and, perhaps, taking into account for further use only those points where such a correlation occurs.

4. Experimental studies

4.1. Algorithm of determining the displacement of the aircraft based on the analysis of two consecutive images from the target load cameras of the unmanned aircraft during movement

Let the analysis be subject to the video from the observed camera, the field of vision of which is directed vertically downwards. For two consecutively received frames with a frequency of, for example, 5 seconds, it is necessary to calculate the displacement, namely the real distance that was covered in the interval between the frames and the direction of movement.

For more accurate calculations, you can add a check of the value of the angle of inclination of the machine (roll and pitch), and use only those frames that were recorded at the time when the inclination of the machine was released. Provided that the image is obtained too much due to long, large angles of inclination, which allow when turning or caused by weather factors, it is possible to stop the movement, until the moment when it is recommended that the leveling takes place. At a sufficiently high altitude, or a low speed of movement, an increase in the interval between receiving frames for processing is possible.

A special factor that can affect the quality of determining the distance traveled by an aircraft is the case when the image is subjected to various deformations such as fish-eye or distortion.

Distortion is primarily able when using zoom lenses, and the higher the zoom ratio, the more able it is. In addition, the level of changes may vary depending on the distance to the object, in some cases a close object may be distorted, while a distant one will be without deformations.

Thus, only the central area of the image, which is approximately 50-70% of the area of the entire image, can be recommended to be used to determine special points. The specified approach should contribute to reducing the calculation error caused by deformations.

Before starting processing, it is also a desirable procedure to scale the received image by reducing it, which helps to reduce the load on the image processing microcontroller. For example, you can recommend reducing the image to 600x480.

Taking into account the comments made about the image received from the cameras of the target load of the aircraft, it is possible to proceed to its processing in order to determine the displacement.

Let's consider the algorithm (Figure 1) for calculating the displacement of the aircraft in more detail with a description of each step. Let B1 and B2 be a set of singular point descriptors and corresponding pixel indices of two consecutive images

$$B_1 = \{(m_k^1(i,j), \theta_k^1(i,j); i = \overline{-3,3}, j = \overline{-3,3}), (i\_pos_k^1, j\_pos_k^1), k = \overline{1, M_1}\},$$
$$B_2 = \{(m_{kk}^2(i,j), \theta_{kk}^2(i,j); i = \overline{-3,3}, j = \overline{-3,3}), (i\_pos_{kk}^2, j\_pos_{kk}^2), kk = \overline{1, M_2}\},$$

and array B1 was received earlier than B2.

Algorithm. Determining the displacement of the aircraft based on the analysis of two consecutive images from the target load cameras of the unmanned aircraft during movement.

Step 1. The first step is to get a zoomed image from the camera.

Step 2. We define arrays of special points on the image and their descriptors.

Step 3. We check whether there are points and descriptors for comparison.

Step 4. If there are no points for comparison (possible only when processing the first frame), remember the points found (see Step 2) and their descriptors as points for comparison. We get a new image and go to point 1.

Step 5. If there are special points for comparison, we compare their descriptors in order to detect points that are present in the images.

Step 6. We subtract the pixel indices of pairs of points that coincide on images, thus obtaining a set of displacements along the width and height of the image for each of the key points.

Step 7. We average the values obtained in point 6 of the value, thereby obtaining an estimate of the average displacement of local features:

$$\overline{i\_pos} = \frac{\sum_{i=1}^{T}(i\_pos_i^1 - i\_pos_i^2)}{T}, \overline{j\_pos} = \frac{\sum_{i=1}^{T}(j\_pos_i^1 - j\_pos_i^2)}{T},$$

where T – the number of coincidences of singular points in two images.

Step 8. Based on expression $m = \frac{d}{\left(\frac{res}{ms}\right)}$, we calculate the value of the distance per 1 pixel of the image (to reduce the number of calculations, we check for a change in height, and if the height has nspecial points changed or has changed insignificantly, we leave the previous value of the distance).

Step 9. Multiplying the values $\overline{i\_pos}$ and $\overline{j\_pos}$ obtained (see clauses 8 and 7) and we get an estimate of the average displacement of the camera relative to the earth's surface for the time that has passed between the moments of receiving frames.

A conclusion about the direction of movement of an unmanned aerial vehicle can be made based on the sign of the obtained estimates $\overline{i\_pos}$ and $\overline{j\_pos}$

Step 10. We save the found (see Step 2) points and their descriptors as points for comparison. Let's go to Step 1.

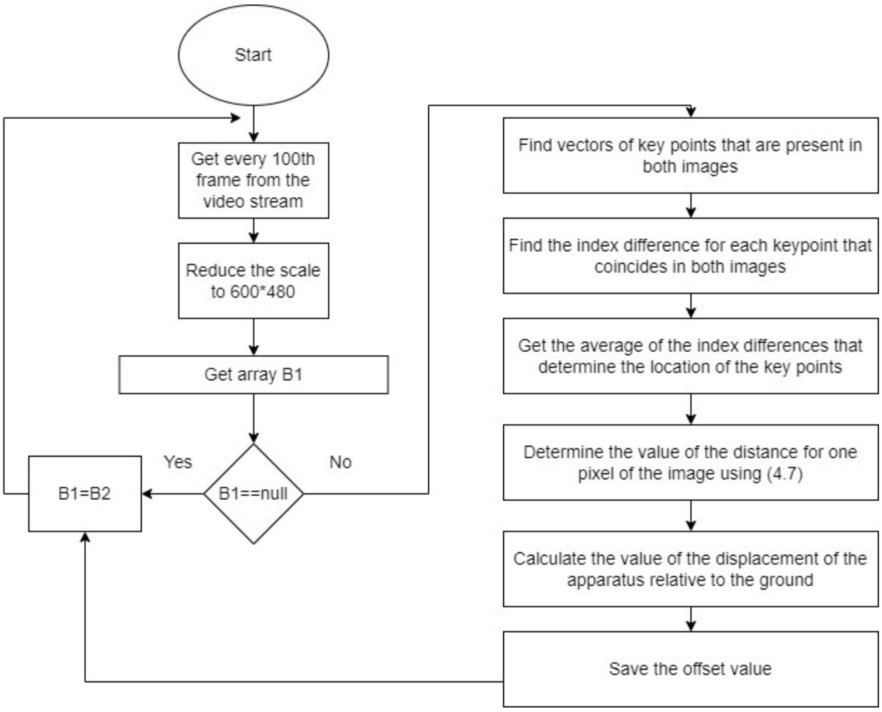

Figure 1: Block diagram of the displacement calculation algorithm.

Thus, using the given algorithm, it is possible only to estimate the distance the aircraft has moved, but also to obtain the direction of such movement. Therefore, by fixing these indicators during the flight task, it is possible to obtain an estimate of the location with reference to the coordinates. However, the latter is possible only after the orientation of the initial image has been performed. In addition, the given algorithm can acquire refinements for the case of performing various types of maneuvers by an aircraft, so practical studies of this issue go beyond the scope of the purely theoretical material of the current section.

4.2. Simulation testing of the technology of navigation of an aircraft using an optical channel

4.2.1. Flight simulation on test images

The essence of the simulation is to replace the input video stream: instead of a real flight, test images are used with dimensions that significantly exceed the resolution of the video camera.

Accordingly, the real flight is replaced by a sliding window (simulation of the field of vision of the UAV camera [1]) according to the specified test picture, and the movement of the UAV is replaced by the movement of the sliding window in the corresponding direction. Figure 2 shows an example of a test picture used for simulation testing. In order to test the proposed approach, appropriate software was developed [18]. The main window is on Figure 3.

Figure 2: An example of an aerial photograph of an area that used for testing. The size of the photograph is 8176×6132 pixels.

Figure 3: The main window.

In the selected zone 1 of Figure 3 there are parameters for the filtering method of special points.

To set the signal loss point, press "Set GPS signal loss point", and to set the base - "Set base". After that, we get the result, which can be seen in Figure 4.

After that, if the user presses the "Next step" button, the process of positioning the drone and returning it to the base is described in the previous part. Namely, first the drone searches for its position (Figure 5), after which it flies straight to the base (Figure 6).

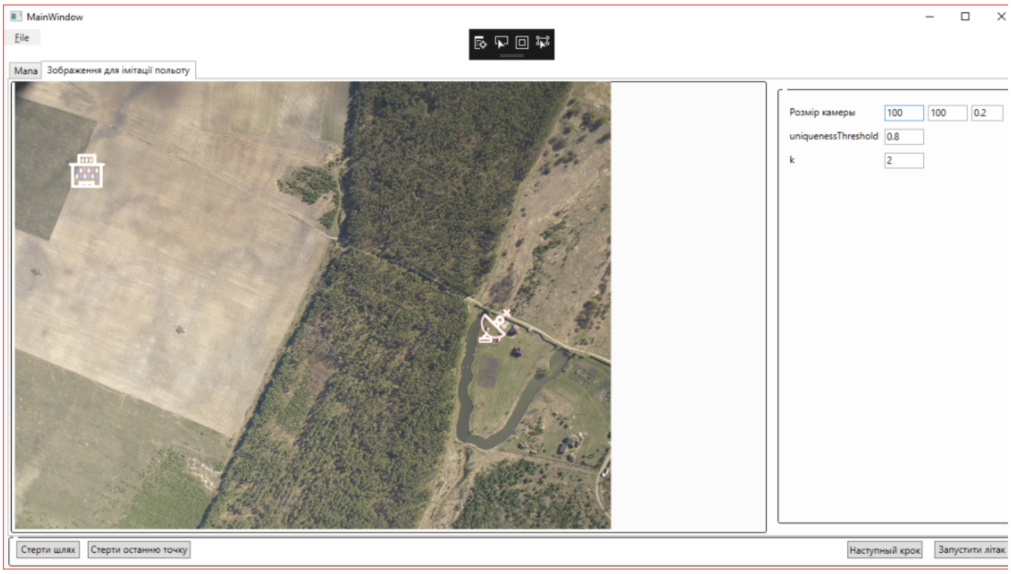

Figure 4: Setting the base and point of loss of the satellite signal.

Figure 5: Simulating the flight of the UAV along the Archimedean spiral to find the position.

Figure 6: Simulation of the UAV flight to the base.

4.2.2. Results of simulation testing

The result of the first test can be seen in fig. 5, 6. They show that the drone will return to the base if there is enough information on SPECIAL POINTS from the map and a clear enough picture from the drone itself. It can be seen that due to the small size of the UAV camera, it took a long time to find the position, as the drone flew in a spiral for a long time.

When the size of the image from the camera increases, the speed of finding increases, and the possibility of correcting the location increases, as can be seen in zone 1 of Figure 7.

Figure 7: Testing in the case of a UAV flight to the base with an enlarged image from the camera.

When the drone flies for a long time without determining the position during the flight, the position search takes place again (Figure 8). It can be seen that the developed algorithm works correctly, but position search is required.

Figure 8: Testing in the case of a long journey without determining the position during the flight.

Testing was also conducted on different images with different image quality (Figure 9). It has been confirmed that the method works on different images, and although it depends on the quality, it can handle low-quality images.

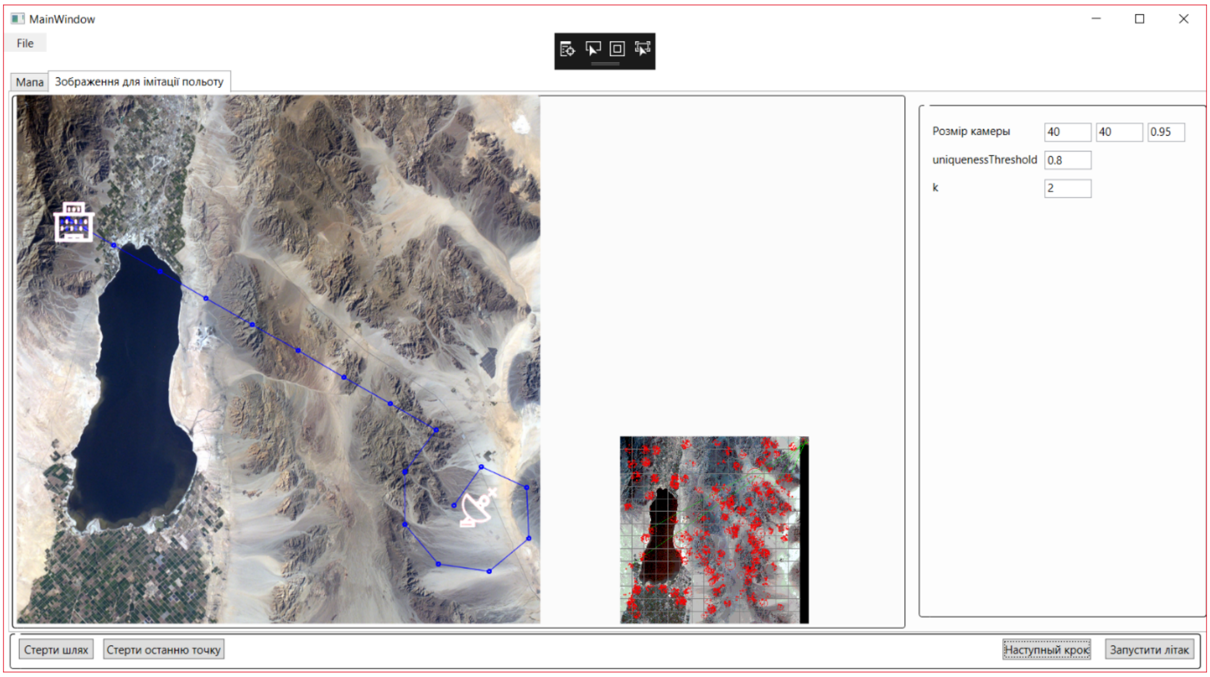

Figure 9: Testing on lower quality images.

Thus, as a result of performing a simulation test of the method proposed in this section, the expected results were obtained, which confirms its correctness.

5. Conclusions

Mathematical support for the navigation of an unmanned aircraft along an optical channel must take into account the objectively existing limitations associated with the hardware capabilities of the on-board computer and a number of assumptions. The formal stages of determining the position of the aircraft and the conditions for their implementation have been formulated.

The procedure for determining the coordinates of special points during a flight mission and preparing data for further analysis in order to determine the position of the aircraft is presented in detail.

For the first time, a method of preliminary determination of the coordinates of the aircraft based on the non-parametric estimation of the two-dimensional density function of the distribution of the coordinates of special points is proposed.

A method of verifying the reliability of the previously determined position of the aircraft based on the evaluation of the consistency coefficients of the determined coordinates of special points of the image and their actual position on the image is proposed.

Approaches to solving the problem of estimating the location of an unmanned aircraft in cases where it is not possible to reliably determine the coordinates based on the proposed method are defined. In particular, the procedure for recording changes in the position of the aircraft based on the analysis of consecutive frames of aerial photography has been formalized.

The software was developed to perform a simulation test of the proposed aircraft navigation technology using an optical channel. A description of the structure of the developed software is given.

Simulation testing was performed using the developed software. Correctness of operation of the proposed technology on different images and in different situations has been confirmed.

Taking into account the confirmed correctness of the proposed method and the proven technology of the automatic control of the aircraft, further research should be directed to their unification and the creation of a suitable unmanned aircraft with the possibility of autonomous navigation along the optical channel.

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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