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DETERMINING THE INVARIANT OF INTER-FRAME PROCESSING FOR CONSTRUCTING THE IMAGE SIMILARITY METRIC

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The relevance of modeling digital images is determined by the need to implement approaches in the study of localization and identification of objects in order to reduce the amount of data. In this paper, the study object is the topology of a discrete two-dimensional image within the framework of the problem of determining the invariants of diffeomorphic transformations. Geographic information objects (GIOs) refer to objects that are on a given surface or objects that locally change the surface. With regard to objects, it is assumed that the change in their geolocation in the process of forming both single images and an extended series of frames obtained in the process of continuous monitoring is insignificant. In the process of scanning the surface, possible changes in the position of the image source are taken into account, for example, such as yawing, rolling, and pitch in the case of unmanned aerial vehicles (UAVs). These maneuvers are represented as a group of diffeomorphisms that are controlled by the internal gyroscopes of the carrier and the external navigation system. Based on the studies reported here, the initial ontology of digital images (ODI) has been determined by using the model of color spaces and functions of a special kind. The presence of an ontology makes it possible to build an adequate topology of color distribution in the image and take into account the specificity of the distribution of different colors in a digital image. The study results indicate that a promising method is to determine the similarity by constructing a color atlas structure graph (CASG) based on ODI and by determining invariants as a fragment of CASG inherited by all images in the sequence. The scope and conditions for the practical use of the result include its application to the analysis of images by methods of artificial intelligence

***Keywords:** digital image, color atlas, geographic information object, ontology, measure, similarity, hash function, diffeomorphism, persistent homology*

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1. Introduction

GIOs refer to objects that are on a given surface or objects that change the surface locally. With respect to these objects, it is assumed that the change in their geolocation during the formation of both single digital images of GIO portraits and over a long series of images obtained during continuous monitoring is insignificant. Real-time accounting, which arises from the need to process the flow of images in the process of inter-frame processing of surface scanning, leads to a sharp increase in the required amount of computing equipment and the time spent on calculations in general.

One of the factors in determining the similarity of GIO images is the presence in the image of special points or special areas in terms of brightness, color, or shape, the location of reference points based on the available geodetic references of the object. Such points include, for example, marks remaining after construction, or geodetic marks of the object. They can be determined based on preliminary information about the location of GIO images. The above makes it possible to determine the linear and altitudinal dimensions of GIOs.

The synthesis of new models, methods, and devices for monitoring geoinformation objects in this subject area will help successfully meet modern requirements for video information systems.

Research aimed at expanding the application, improvement, and development of methods for collecting, processing, and representing large amounts of data in real time for the tasks of monitoring GIOs using UAV tools and web cameras is increasingly significant and relevant. The representation of an image in the form of a diagram makes it possible to process large amounts of information.

2. Literature review and problem statement

Paper [1] discusses the problem-oriented perspective and provides a comprehensive overview of both superficial and deep transfer learning methods for visual recognition between data sets. A comprehensive problem-oriented review of advances in transfer learning in relation to this problem revealed not only problems in transfer training for visual recognition but also those that have been almost not studied. Paper [2] discusses the most recent developments in deep learning techniques for semantic segmentation of remote sensing images, including unconventional data such as hyperspectral images and point clouds. Emphasis is on improving pixel-level accuracy. It is noted that the emerging methods of deep learning have demonstrated significantly improved performance on several publicly available data sets. Based on the analysis and classification of recognition problems between data sets and the application of the semantic approach [1], it is possible to state the importance of the task of searching for digital image invariants during inter-frame processing [2, 3]. Paper [4] notes that in recent years there has been exponential growth in the processing and transmission of video over the Internet and other applications. However, improving video compression while maintaining the same quality requires further research. The problem of the need to develop approaches and methods that minimize the number of calculations, which makes it possible to increase the efficiency of systems for transmitting and recognizing video information streams, is also drawn attention to in works [5, 6]. Paper [7] discusses modern methods for implementing joint compression of video and other visual streams together with targeted analytics in a wide range using artificial intelligence. To solve this problem, works [8, 9] propose methods of joint compression of the video sequence, taking into account the features of the entire time range (end-to-end technology). The above works also consider the use of methods of intelligent processing of data representing a digital image.

Existing intelligent methods of inter-frame image processing are based on deep learning [10, 11]. Also, for these purposes, steganography methods are used to extract image information [12]. However, these methods require large computing power and large amounts of high-quality initial data.

A promising method of encoding video in the feature space (FVC), and not in pixel space, is considered in work [13]. The study of the application of new methods based on the consideration of structural features (topology based on color atlas) is reported in [14, 15]. The combination of these methods with methods of rapid processing increases the efficiency of video surveillance systems.

To study the motion of systems in the frequency range of 50–100 Hz, the method of reducing complex discrete-continuum equations is applicable [16].

All this allows us to assert that it is necessary to develop new digital methods and devices that differ not only in efficiency and quality but also in the speed of computation by reducing the amount of necessary calculations by encoding video information signals.

3. The aim and objectives of the study

The aim of this work is to determine the invariant of inter-frame processing of the time sequence of GIO images obtained from the UAV web camera to determine the metric of image similarity and the necessary initial information.

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

– to investigate the elements of the initial ontology of the digital image, which determine the initial information received from the web camera, taking into account possible changes in the shooting point, for example, UAV maneuvers, which have recently become widely used as carriers of optical equipment;

– to build a topological scheme for the representation of a digital image, providing objective characteristics of dynamically changing in time scenes of geoinformation objects based on the ontology of the initial level of the image (ISO).

4. The study materials and methods

During the study, methods of processing digital images, methods of system analysis, methods of cluster analysis, methods of the theory of structures (homological algebra) and relations theories, methods of topology, methods of graph theory, methods of geometric hashing, methods of computational and discrete geometry were used.

The initial information for achieving the goal contains the following:

– images contain background (stationary part of the signal), random noise, and GIOs;

– the statistical characteristics of the background vary significantly over the field of the frame: the dispersion of the background, the rate of decline of the form of the correlation function. Correlation dependences are anisotropic: the correlation in the direction of scanning exceeds the correlation along the scanning ruler;

– the random noise accompanying the measurements has the same order of magnitude with one division of the signal quantization scale and is stationary in frame and in time, the nature of the noise distribution is close to normal;

– GIO and its shape is modified depending on the location relative to the elements of the scanning ruler;

– frames of the same sequence are not brought to a single coordinate system, along the ruler, the frame is shifted by less than its size;

– temporary stationarity of the background is observed only on two or three frames of one scanning direction;

– the temporal stationarity of the noise of objects and backgrounds during forward and reverse scanning are significantly different;

– images can contain glare.

Geographic information objects are considered to be localized on a given surface, a horizon line is present, and the light source is localized as a limited elliptical region, or an area extended along the image. As a result of the transformation of the image into a halftone, a system of light and dark spots appears on it, corresponding to the distribution of shadows and illuminated sides of the GIOs, as well as internal depression areas. The set of image-fixations of the geographic information object consists of sets obtained as a result of the drift of the web camera vertically, horizontally, in azimuth relative to the GIO area.

To determine the transformations to the basic orientation of the web camera, the following parameters should be taken into account: yaw, roll, and tonnage of the shooting frame, which are controlled by the internal gyroscopes of the carrier and the external navigation system. It should be especially noted that the area of localization of GIOs is long. Because of this, the accuracy of the positioning of the web camera at the point of image formation relative to the surface of the GIO location becomes an important factor. Camera positioning can be carried out through satellite navigation and binding to the object's references.

As a result of converting images into a GrayScale model, it becomes possible to determine the location of light sources or areas with increased luminosity, which, in particular, makes it possible to determine the totality of local brightness gradients. A set of local collinear gradients of brightness from areas in the image makes it possible to identify shadows from GIOs or illuminated surfaces. It is noted that when the motion of the web camera changes, collinearity in the field of local brightness gradients is preserved as an invariant.

Another invariant of converting images to the GrayScale model is the ratio of the sizes of the different regions for each GIO in the luminance channel.

The transformation invariant that allows the GIOs to be highlighted against the background of the image is the preservation of the local area containing the anomaly of the brightness gradients in accordance with the distribution of brightness on it. At the same time, not only towering objects above the surface level are highlighted but also holes (depressions).

5. Results of investigating dynamically changing scenes of geoinformation objects based on the ontology of the image

5. 1. Investigating elements of the initial ontology of the digital image of the initial information obtained from the web-camera

When considering this issue, the results of work [17] were employed. By analogy with [17], the tasks of creating an image ontology (ISO) include:

– the creation of a holistic knowledge system that provides information support to specialists and experts in various fields in which ISO is used or researched;

– the image is a complex, informationally combined field of knowledge. Therefore, its ontology should form a subject area with the ability to provide automation of output within the intellectual knowledge base of ISO. The resulting knowledge base should allow the construction of intelligent (automated) recognition and classification of the corresponding ISO;

– since the knowledge base in the ontology of ISO is integrated from the database of applied areas, therefore, it must provide a synthesis of inference integration algorithms for each specific formalized application problem;

– the ontology of ISO should allow the construction of metrics on a set of ISO in order to apply cluster analysis methods, to develop a computational method for forming an internal catalog of fixed objects on a series of frames.

The practical application of the ontology of the digital image makes it possible, on the one hand, to formalize the description of its structure in the most capacious and complete representation. On the other hand, it is necessary to determine the classes of features, which in turn makes it possible to build adaptive recognition and monitoring algorithms. Localization of GIOs in digital images in the process of monitoring using a dynamic image source, for example, UAVs, is implemented as a procedure for determining a measure of similarity based on the hash functions of the color atlas structure graphs (CASG) of images. At the same time, the scheme is CASG, in which all the edges are single.

The ontology of the initial level of ISO is a synthesis of knowledge bases of discrete geometry, photogrammetry, taking into account the internal hierarchy of classes of concepts and semantic relations in these classes, and is the initial development of ontology. It is built based on the methods of the theory of structures and the theory of relations.

The construction of an ontology is followed by its refinement based on classification diagrams of compositional schemes, relationship schemes, and diagrams of the state of objects. These steps are a structured methodology for developing, supporting, and studying ontology.

The definition of a measure of ISO similarity provides additional possibilities for identifying GIOs through the use of a color atlas of the image. In the case of low light of the object, the color atlas is the main factor since it makes it possible, through coloring, to determine the boundaries of GIOs that appear in the background or, as reflexes, in the color of the adjacent object in the image.

The use of color in the analysis of a GIO image makes it possible to identify small structures and poorly structured areas due to the fact that chromaticity is a representable feature of the image, even in the case of low brightness.

From the point of view of the color atlas, the image of GIO is the following aggregates:

– color spots of different structures (gradients, colors, patterns);

– boundaries between color spots;

– adjacency relations set on a given set of spots;

–absolute values given by the functions of the presence of the spot;

– mutual proportions.

The synthesis of the initial ontology of the color regions of ISO, containing the terms, objects, processes, and their characteristics that make up the thesaurus (vertices of the graph) of the ontology of ISO includes:

1. Universum – direct digital image of the object on the image medium.
2. Color palettes on the image medium.
3. Image media topology, connectivity, touch, neighborhood, area.
4. Structures on the image media.
5. Clusters on the image media.
6. Features as functions on the image carrier.
7. Parameters on the image media.
8. Descriptors on the image media.
9. Figures on the image medium.
10. Noise and noise structures on the image medium.
11. Background on the image media.
12. For areas: colors, gradients, textures.

In order to illustrate the ontology of ISO, the ontology model is represented in the form of a graph, where arcs indicate the relationships of terms and rules that describe the relationships (is-A connections).

5. 2. Construction of a topological diagram of dynamically changing in time scenes of geoinformation objects

The task of processing visual information in real time when scanning a surface is multiparameter as it requires taking into account many different features and factors. In the process of monitoring geoinformation objects, it is necessary to take into account the following features:

– the shape of the GIO is significantly modified depending on its location relative to the elements of the scanning ruler, and the brightness changes tenfold;

– frames of the same sequence are not reduced to a single coordinate system;

– temporary stationarity of the background is observed only on two or three frames of one scanning direction;

– descriptions of noise, objects, and background during forward and reverse scanning differ significantly from each other;

– images can contain so-called “glare” – bright, slowly moving areas from frame to frame;

– the solution of the problem of classification of GIOs is difficult due to various kinds of distortions, the absence of key points of the elements of group point objects with a shape and internal structure;

– the selectable fragment size has a significant impact on the amount of calculations;

– real-time accounting arises in connection with the need to process the flow of images to the level of decision-making;

– the continuity of the input data stream imposes restrictions on processing time, which leads to a sharp increase in the time spent on computations as a whole.

In order to reduce computational costs, the raster image is represented in the form of a topological diagram. To build the diagram, topology methods for incident areas and mathematical graph theory were used.

For each spot of this GIO ISO, point O_i is defined (Fig. 1) so that together these points are representable to the color spots of this image [14, 15]. It should be noted that in this approach, the background is nothing more than a separate distributed object in the image. At the same time, it may be incoherent and does not require a special definition as a "background".

Based on the color atlas of the GIO image, a structure graph (CASG) is constructed, the vertices of which are above certain points, and the two vertices are connected by an edge if the color spots defined by these vertices are adjacent.

The CAS graph has the following properties:

– the top of the CASG with one edge corresponds to an isolated region within another region, an isolated edge region;

– the associated area of color spots is represented by CASG cycles;

– each vertex is assigned a number;

– the vertex has a color corresponding to the color containing its area;

– the edges of the graph connect adjacent regions;

– adjacency – along the boundary; by touch;

– edge load – the length of the common border with the adjacent region;

– the structure of the adjacency of the vertex: the order of adjacency of the edges is given; regions are touched; multiple touches;

– the multiplicity of the edge – the degree of point of contact of the areas by adjacency;

– bypassing the boundary of the area sets the direction of bypassing the ISO as such;

– alternation of simple edges and vertices and multiple edges. There is a simple edge between the multiples of the edges;

– ordering of multiple edges according to the color of the vertices, they connect, cyclic;

– the repetition of the same colors in the loop corresponds to the same color areas at the point of touch but they are not adjacent in border (do not have a common length boundary greater than unity).

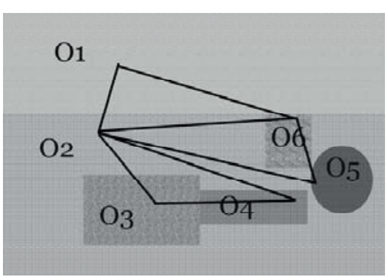

Fig. 1. Example of plotting the structure graph of a color atlas

Each region is represented by the following tuple of values: the area $Ob_i \overset{def}{\Leftrightarrow}$ {number as name; color from a given color wheel; number of touches and their degrees; number of border segments; boundary structure with cyclic permutation accuracy – touch segments}. Let's denote an image of a GIO as *IMG*, then partitioning $IMG_j \equiv \bigoplus_{i=1}^{n_j} Ob_{ji}$ is a direct algebraic sum of regions.

Intersection of regions

$$IMG_{jm} \bigcap IMG_{jl} = \Delta IMG \neq \varnothing \left(m \neq l\right) \Leftrightarrow:$$

1) $\forall Ob_k \in \Delta IMG \Rightarrow \left\{Ob_k \in \left\{Ob_i\right\}_l\right\} \wedge \left\{Ob_k \in \left\{Ob_i\right\}_m\right\}$;

2) $\exists S_n$ – repainting the vertices IMG_l or IMG_m on the color wheel while maintaining the adjacency of colors and the adjacency of areas;

3) in the presence of motion (d), the shift of IMG_l relative to the recorder to IMG_m is defined as $\Delta IMG = d(IMG_l)$ and GTA from:

$$\Delta IMG \in \{ГСЦА(IMG_l) \wedge ГСЦА(IMG_m)\}.$$

Then:

– $\{d_{li}\}$ – the set of movements of the recorder with respect to fragment l;

– $\forall i, d_{li} \prec d_{li+1}$;

– $d_{lT}\left(\ldots d_{l1}\left(IMG_l\right)\ldots\right)$ is the trajectory T of fragment l.

For any unclosed trajectory T, the following is true:

$$\exists n_l^T : d^T_{n_l^T}\left(\ldots\left(IMG_l\right)\ldots\right) = \varnothing,$$

n_l^T is the depth of the fragment l relative to the trajectory T.

For any closed trajectory T, the following is true:

$$\exists n_l^T : d^T_{n_l^T}\left(\ldots\left(IMG_l\right)\ldots\right) = IMG_l.$$

Then ΔIMG_l^T is the monitoring invariant relative to trajectory T, where:

$$\forall i = \overline{0, n_l^T} : \left\{\Delta IMG_l^T \neq \varnothing\right\} \wedge$$
$$\wedge \left\{\Delta IMG_l^T \in d_{li}\left(\ldots d_l\left(IMG_l\right)\ldots\right)\right\}.$$

The comparison of CASGs for different images of GIOs as graphs gives a measure of the similarity of the structures of different images based on their color regions.

It is noted that due to the color atlas of the image of GIOs, it is possible to display local anisotropic features as independent changes at each point of the image, forming a heterogeneity between the locations of the corresponding spots.

The construction of the procedure for bringing a set of images of GIOs taken along one trajectory of movement of the web camera to one angle is carried out by comparing the angles of the optical axis of the cone of view to the surface at different points of the trajectory. This procedure is implemented through the diffeomorphisms of the color atlas.

Frame-by-frame overlap of the GIO image ensures continuity of monitoring while tracking the projection of the trajectory of the web camera on the surface of the GIO location. Taking into account the timing scale for individual segments of the projection, it is possible to reproduce the relief of color spots of the "lidar" type.

Cross-linking of GIO images is implemented by tracking the shift of the view cone and image change, as a set of related points of areas migrating from one frame to the next (Fig. 2, where T_1, T_2 are the points of the camera position in time).

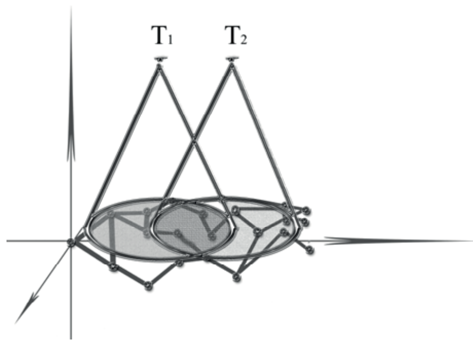

Fig. 2. Tracking the shift of the overview cone and changes in the color atlas structure graph

Due to the constructed color atlas of the image of GIOs, it is possible to represent the movement of the web camera as a collinear displacement of a set of representable points of spots-areas. In this case, the symmetric difference in the image of a GIO of the same spot between its two images, as the oriented collinear displacement is the direction of movement of the web camera, the totality of all the spots of the image determines the field of gradients. Along the direction of travel, the initial CASG fragment has disappeared, and the final fragment is moving. The initial fragment of GCAC is reduced frame by frame until it disappears completely.

Along the motion path, the depth (the number of consecutive frames containing the fragment) of the ISO fragment matches is maximum.

Using the color atlas method for the image of GIOs, a sequence of color portraits is constructed taking into account the local gradients of color and the shape of the single-color local area. The resulting color portraits of the GIO image in conjunction with the location and orientation of the web camera make it possible to build a dynamic series of changes in its color atlas. In terms of the color atlas of an image, it makes it possible to construct or define the designs of areas in the image and the shape sets of areas inherent in each particular row. At the same time, the invariant for determining the similarity of the areas determined by a representative set of points on a given portrait series, taking into account rotations and azimuth removal, is the preservation of proportions between them.

One of the factors in determining the similarity of GIO images is the presence of images of special points or special areas in brightness, color, or shape, which can be determined based on preliminary information on the location of GIO images.

To detect a feature description of an image, it is necessary to bind to its local features – special points. A special point, or feature, is an image point that satisfies a number of properties:

– certainty;
– robustness;
– invariance;
– stability;
– interpretability;
– the number of detected special points should provide the required number of them for the detection of objects.

Also, to determine reference points, it is possible to use information based on the available geodetic references of GIOs left after construction, or geodetic marks of the object.

The above (a priori information and local properties of a particular point) makes it possible to determine the linear and elevation dimensions of GIOs.

Modern UAV web cameras have rangefinders, altimeters, and gyroscopes, which, together with positioning equipment, make it possible, together with positioning equipment, to accurately record the location of the center of gravity and the orientation of the web camera platform. This makes it possible to highlight a cone around the optical axis of the web camera, which scans the GIO on the surface. As a rule, the inner cone of the survey is known, which has the same optical axis and apex. This cone is determined from the condition of exclusion of marginal distortion in the cone of the review.

Pitch, yaw, and roll conversions can cause the image of GIOs to scale. This creates image fragmentation by excluding part of the image from the view cone, or by attaching previously unrecorded GIO fragments to the web camera's view cone.

Let's introduce the following symbols:

– $T(t_i)$ – conversion of the GIO image due to pitch at time t_i;

– $P(t_i)$ – conversion of the image of GIOs by yaw;

– $K(t_i)$ – conversion of the GIO image due to the roll of the web camera frame;

– $\{t_i\}_{i=\overline{0,N}}$, $t_i<t_j$, $i<j$ – moments of fixation of the GIO image, and the exposure time is determined from the conditions of clarity of the image for this web camera and the linear speed of its movement in E^3, and ensuring the commutativity of the transformation T, P, K for all eight possible combinations of 3-termed sequences.

Let $Or(t_i)$ be the orientation of the web camera at time t_i. Then its orientation at the next point in time is defined as $\forall i, \exists j : Or(t_{i+1}) = Dr_j(Or(t_i))$, where Dr_j, $j=\overline{1,8}$, Δt are possible three transformations.

Topological relations between points are more resistant to image transformations, do not depend on the coordinate representation of the form under consideration and are invariant with respect to diffeomorphic transformations. The implementation of the comparison of the similarity of CASG images is based on computational topology algorithms for objects represented by sets of points [18]. For this purpose, for example, the method of geometric hashing and similarity comparison based on Hamming distance (a method widely used in computational geometry to compare images [19]) is used, in conjunction with the pHash perceptual hashing algorithm. A distinctive feature of the use of the pHash comparison method in relation to the methods of algebraic topology is the receipt of invariants of large amounts of data, finding the distance between images by entering non-geometric information about the distances between them. When comparing images, hash values are compared using coefficients of difference or similarity between two perceptual hash values.

The development of the application of persistent homologies for CASG is investigating invariants of large data volumes. The use of persistent homologies makes it possible:

– to increase the amount of information about the shape of the object;

– to provide the possibility of constructing a diffeomorphic mapping with the formation of metamorphosis, in which the images are not diffeomorphic and have different topological characteristics;

– to find the similarity coefficients of images;

– to develop a method that is resistant to various modifications of images.

6. Discussion of results of investigating the interframe processing invariant for the construction of an image similarity metric

A feature of the proposed method and the results obtained on its basis is the construction of a topological scheme (invariant) of interframe processing of a digital image based on topological features.

The results of the research indicate that by constructing a graph of the structure of the color atlas based on ODI, a measure of similarity as a metric of structures is realized. An invariant is defined as a CASG fragment that is inherited by all sequence images (Fig. 2). The search for new invariants of the sequence of images in time is a promising method.

The peculiarity of the proposed method and the results obtained is the application of ODI ontologies in conjunction with the pHash perceptual hashing algorithm.

More research is needed on the dependence of the speed of image invariant processing on the factor of detail and color space, the height and frequency of image formation, the construction of image processing processors.

The disadvantages of this study include the need for additional studies of UAV recording facilities, which have a limitation in terms of considering specific implementations. However, this can be leveled by defining and applying minimum requirements for the registration means of UAVs of different types.

The proposed approach can be successfully developed and applied to the analysis of images by methods of artificial intelligence, learning neural networks, automation of knowledge assessment, knowledge engineering, which are widely used in different countries of the world, including Ukraine.

The subject of further research is the experimental confirmation of the theoretical results obtained in the current work.

The conducted research based on the ontology of the initial level of the image makes it possible to provide objective characteristics of dynamically changing in time scenes of geoinformation objects. The advantage of the presented method is the possibility of including in the search procedure not only additional features that make it possible to clarify the class of CASGs but also various logical or heuristic rules, as well as analytical expressions describing this subject area. The use of tools of logical, heuristic rules, and analytical expressions will make it possible to adjust the assessment of the values of the CASG features in a necessary way and increase the reliability of solving problems.

7. Conclusions

1. The initial ontology of the digital image is determined based on the initial information obtained from the web camera, taking into account the dynamics of the position of the optical source, for example, UAV. Thus, the objective characteristics, dynamically changing in time scenes of geoinformation objects are taken into account.

2. A topological scheme representing digital images of inter-frame processing of a temporary sequence of images (topological scheme) taken by a web camera has been constructed, which makes it possible to track the inheritance of primary source information. The constructed scheme is an invariant that is simultaneously resistant to diffeomorphic transformations of images and has an acceptable speed of operation in determining the similarity of the image.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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