

This study examines the set of processes aimed at improving the efficiency of steganographic methods for information protection, while ensuring a specified level of integrity and timeliness of transmission in infocommunication systems. The work addresses a scientific and applied task of increasing the level of information security while maintaining a specified level of integrity and timely delivery of data from unmanned aerial systems (UASs). It relates to the existence of a contradiction between ensuring the confidentiality of video information and the efficiency of its delivery with a given integrity.

In the process of research, a method for structural steganographic embedding has been devised, based on changing the values of positional basis (PB). The difference is the embedding of information in the process of modifying the PB values, taking into account the detection of structural dependences in the spectrally modified space of a video container (VC). Such transformations are carried out under conditions of reducing the influence of spectral space modifications on the compression level. The above advantages make it possible to build a comprehensive method of steganographic transformations in the process of VC compression.

The method is distinguished by two principal aspects. The first is the use of a sequence of steganographic transformations in independent spaces to detect dependences that are used in the process of embedding information. The second is that information is embedded in the structural-spectral space, taking into account its modification by the youngest bits. This enables increasing the level of steganographic capacity by an average of 7% without distorting the integrity of the stegano-containers and removing hidden information on the receiving side.

The devised method is intended to be used to improve the confidentiality, efficiency, and integrity of video information delivery from unmanned systems

Keywords: unmanned aerial systems, infocommunication systems, video-container, redundancy, structural dependences, positional basis

DEVISING A METHOD FOR COMPLEX STEGANOGRAPHIC EMBEDDING OF INFORMATION IN THE STRUCTURAL-PSYCHOVISUAL SPACE

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1. Introduction

Further development of existing and the design of promising high-tech concepts is a characteristic feature of moder-

nity. Intelligent robotic systems are also actively evolving. One of the areas of their application is remote acquisition, analysis, and delivery of video information. Such service is used in the interests of ensuring national security and

defense, improving the quality of functioning of critical infrastructure, search and rescue operations in emergencies, as well as for various commercial purposes.

Depending on the specificity of using such information services (INSSs), appropriate requirements are put forward for their qualitative characteristics.

At the same time, contradictions arise in the process of achieving the required characteristics of INSSs. Such contradictions acquire the greatest significance in case of need to provide information advantage under conditions of active counteraction. There is a need to simultaneously ensure the efficiency of delivery and confidentiality (protection) of video information with a given integrity and distribution capacity.

In this case, solving such tasks using unmanned aerial systems (UASs) encounters a number of certain difficulties. They are mainly due to the insufficient productivity of information and communication means of unmanned systems for processing and transmitting information. Under such circumstances, a contradiction is outlined concerning the following:

- on the one hand, ensuring the confidentiality of information is accompanied by additional time delays for processing and an increase in the volume of data [1];

- on the other hand, ensuring the efficiency of delivering video information with the required integrity under conditions of limited transmission speed raises the issue of reducing the complexity of processing and/or reducing the bit volume [2].

This justifies the relevance of the scientific and applied task to increase the level of information protection at a given level of integrity and the efficiency of its delivery from unmanned systems.

2. Literature review and problem statement

The most common approaches to ensuring the protection of video information include:

- cryptographic protection methods;
- information hiding methods using steganographic transformations.

Video information protection using cryptographic methods mainly involves the use of a sequential scheme. In this case, a sequential transformation of video data is performed. First, video image compression is used, and then cryptographic transformations are performed. In work [3], the directions of video information protection based on verification of a sequential scheme are considered. At the same time, a sequential video data protection scheme has a drawback. It is associated with an increase in processing time delays and the bit volume of data transmitted from UAS. In [4], an approach to protecting video images during compression is shown. This makes it possible to reduce the disadvantages of a sequential scheme. At the same time, questions arise regarding the presence of fragments with unmasking. This effect is manifested in the case of cryptographic encryption of key information of the compression process. In addition, a common drawback of the above approaches is the increase in the bit volume of data due to the need to use noise-resistant coding.

Hence, under the conditions of limited time of relevance of video information and the presence of requirements for the efficiency of its delivery, there is an interest in the use of steganographic transformations. Steganographic methods provide for their use as a separate component; components

of a complex protection system in combination with cryptography methods. Steganographic methods create conditions for ensuring the confidentiality of information by its hidden embedding in video containers (VCs).

Among the most frequently used steganographic methods are methods for embedding information in the least significant bits (LSB) of VC elements. A typical example of modern implementations of the LSB-information embedding technique is the method described in [5]. Such methods belong to the class of direct steganographic information embedding. The concept of the least significant bits of VCs is understood as those that have a smaller (not significant) impact on the semantic integrity (visual quality) of the restored stego-containers. However, such methods are in conflict with compression methods regarding the use of the amount of psychovisual redundancy. This leads to a trilemma between such indicators as the amount of embedded information; the level of compression; the presence of unmasking factors. An assessment of the balance between the level of steganographic capacity (volume of embedded information) and unmasking factors is carried out in [6]. It is argued that one of the best options for LSB embedding is the domain of discrete cosine transform (DCT) coefficients. At the same time, it is shown that in case of need to increase the steganographic capacity, certain difficulties arise. They are due to the need to ensure the masking of the fact of the presence of hidden information.

Options for increasing the efficiency of LSB embedding methods are considered in [7–9]. In [7], a modern hybrid method for information hiding is reported, based on a combination of LSB mechanisms and the BPCS technique – segmentation of bit planes of video data by their complexity (Bit-Plane Complexity Segmentation). It is proposed to carry out LSB embedding of information only in those bit planes for which a reduction in the unmasking effect will be achieved. Such areas can be fragments of a smooth change in brightness and background areas. However, such areas have limited sizes in video images formed on board unmanned complexes. Accordingly, this limits the potential for increasing steganographic capacity. In [8], a hybrid method based on the use of ChaCha20, wavelet transforms (DWT) and LSB is presented. Balancing between the characteristics of the amount of embedded information, computational complexity and stealth is achieved by choosing a limited number of subbands of the high-frequency region (HH) for the DWT transform. However, this accordingly limits the further growth of steganographic capacity. An option for overcoming such limitations can be the method reported in [9]. The work uses the wavelet transform for LSB-building of information with a reverse channel. That is, a post-inverse wavelet transform is performed. Embedding is performed in each pixel. However, in the compression process taking into account the canting of the spectral-frequency or spectral space, there will be a loss of hidden information. Also, the processing time delays increase significantly. This is caused by the need to perform the reverse and forward wavelet transform operations twice. Another option for increasing the steganographic capacity is the approach described in [10]. There, a method is proposed that includes inverting the LSB of VC pixels with the sum of the corresponding pairs. It is assumed that several stages of information embedding are performed. At the same time, at each stage of the embedding process, the VC of the pixels is inverted depending on the sum of the pairs. However, such embedding does not take into account the subsequent process of video compression and the influence of the quantization

process on preserving the integrity of the hidden data during their extraction. Also, for the proposed approach, there is a significant dependence of the level of integrity of the extraction of data hidden on the receiving side on distortions in the VC region.

An option to increase the efficiency of information embedding by using LSB principles can be based on additional consideration of statistical dependences. This approach is described in [11]. A method of interpolation between pixel blocks is proposed. Then, the method of least significant bits (LSB) substitution is applied using the pixel value differentiation (PVD) method. At the initial stage, the video image is segmented into a 2×2 block, and then the nearest neighbor interpolation (NNI) method is implemented. In the PVD approach, the pixel values of two pixels in a pair are adjusted in such a way that the difference between these two pixel values represents the hidden information. However, an unmasking effect appears in the form of the appearance of false contours. Or vice versa, information hiding leads to smoothing of contour information. To increase the efficiency of message hiding in the contour information area, a method is proposed in [12]. In this case, a fuzzy logic apparatus is used to identify the edges of video image objects. The disadvantages there are as follows:

- the processing time delays for implementing the processes of detecting edges (contours) of video image objects increase;
- during compression, the edges (contours) of video images may become blurred. For example, this is caused by the process of canting spectral components. Such actions will lead to the loss of hidden information;
- there is a need to reduce part of the psychovisual redundancy, which limits the increase in steganographic capacity in the process of further LSB-embedding of information.

Currently, research is under way to improve the efficiency of steganographic transformations based on the use of artificial intelligence models. Examples of this direction are the methods reported in [13, 14]. In these papers, the focus is on the use of generative intelligence models taking into account the features of the stages of the JPEG platform. It is shown that the processes of JPEG compression and steganographic information hiding have a mutual influence on reducing efficiency. In [13] it is proposed to use the artificial intelligence model GAN (ADPGAN), which improves the quality of the restored image. This makes it possible to provide the effect of unmasking the fact of the presence of hidden information. In [14] a new embedding scheme (SE-steganographic embedding scheme) of adversarial steganographic systems based on the use of deep learning models is presented. In this case, the processes of quantization of spectral arrays DCT are additionally taken into account

At the same time, this approach has certain limitations in the case of real-time processing and transmission of video data from unmanned systems. This is due to the following:

- the need to use significant computing and energy capacities for training and functioning of artificial intelligence models;
 - the occurrence of significant time delays for processing.
- However, the capacities of on-board systems in terms of computing and energy resources have certain limitations.

In addition, the general disadvantages of existing steganographic transformation methods are as follows:

1) there is a dependence of the amount of data embedded in the video container (VP container) (steganographic capac-

ity) on the presence of a sufficient amount of psychovisual redundancy;

2) there is an impact on the structural and statistical features of the VC containers, which are used in the process of their subsequent compression.

Hence, as shown in [15], the inadequacy of increasing the amount of embedded information to the psychovisual features of VC containers leads to:

- loss of integrity of video images;
- unmasking of the presence of hidden information;
- loss of compression level and efficiency of video information delivery.

Therefore, existing standardized technological platforms have insufficient capabilities to increase steganographic capacity without loss of integrity. This is especially true in cases of increasing the volume of video data that needs to be processed and transmitted in real time using on-board complexes. This is due to the presence of a contradiction between:

- on the one hand, the limited level of video data compression while maintaining the required integrity within acceptable limits regarding processing time delays;
- on the other hand, an additional increase in processing time delays and video data volumes in the event of ensuring their protection and the required level of integrity.

This contradiction is exacerbated in the case of implementing the information processing and transmission process using unmanned complexes.

Thus, a scientific problem emerges, which concerns the fact that existing methods for embedding information into VC containers have insufficient capabilities to simultaneously increase steganographic capacity and meet the requirements for:

- maintaining the required level of information integrity;
- reduction of compression losses of stegano-containers.

To solve the above problem and ensure the required efficiency of delivery of protected information with the required integrity, it is proposed to devise a steganography method with a complex process of embedding information during compression of VC-containers. It is assumed that information will be embedded at different stages of the compression process using different principles of steganographic concealment. This will create conditions for reducing the share of LSB-embedded data in the total volume of hidden information.

3. The aim and objectives of the study

The aim of our research is to devise a method for complex steganographic information embedding based on taking into account structural and positional dependences in the spectrally modified space of video containers. This will make it possible to improve the level of steganographic capacity under the following conditions:

- reduction of losses in the compression level and integrity of stegano-containers;
- absence of losses for the hidden information extracted on the receiving side.

To achieve the goal, the following tasks need to be solved:

- to devise an approach for developing a method for steganographic information hiding in the compression process based on taking into account a complex of types of dependences of different origins;
- to conduct an experimental assessment of the effectiveness of the complex steganographic embedding method in comparison with existing ones.

4. The study materials and methods

The object of our study is the processes of increasing the efficiency of steganographic methods for protecting information with a given level of integrity and efficiency of transmission in infocommunication systems.

The principal hypothesis assumes that taking into account structural-positional dependences for additional data hiding in the spectrally modified space of video containers could make it possible to increase the steganographic capacity without loss of integrity under conditions of reducing the loss of the compression level.

The basic assumptions adopted in the work include the following:

- the use of structural dependences in the process of constructing the bases of positional systems has the property of steganographic information hiding. At the same time, the need for a reduced amount of psychovisual redundancy is eliminated;

- modification of the spectral space by changing the values of insignificant elements has a limited effect on the length of the codogram in weighted positional systems.

In this study, the process of steganographic transformations refers to the process of embedding information into containers of visual origin (video images, sequences of video segments, sequences of video frames).

As theoretical research methods, methods of digital processing and analysis of video images, data coding methods, steganography methods, methods of compression of containers by their bit volume, coding methods in positional systems are used. To assess the effectiveness of the devised methods and substantiate the adequacy of the results, statistical analysis methods are applied.

In the process of devising information embedding methods, the following simplifications were accepted:

- segments of video images are selected as containers of visual origin for embedding information. Note that the devised steganographic transformation method can be scaled to hide information in a dynamic sequence of video frames;

- JPEG family technology is chosen as the basic standardized platform for video image compression. At the same time, the devised method of complex steganographic transformations can be applied to other compression platforms with segment-oriented processing, for example, JPEG 2000, JPEG-XL, JPEG-XR;

- it is assumed that macro-segment structures are built under the condition of a uniform number of segments of each color component of the YCbCr or YUV model. At the same time, the generated hiding and compression process can be combined to process macro-segment structures of uneven layout;

- the process of segmented compression of color components YCbCr or YUV of a video image and steganographic hiding of information is carried out under the condition of not taking into account their mutual influence;

- it is assumed that the size of video images is chosen as a multiple of the size of segments $m \times m$.

Formalization of the process of devising the method for complex steganographic hiding (CSH) involves constructing the functionality $F(\hat{S}_{t,g}; W_j; m; K_{hid}; L)$, where $\hat{S}_{t,g}$ is a VC container; W_j is a complex of types of structural-psychovisual dependences that are taken into account in the process of steganographic transformations and compression of stegano-containers; m is the size of video image segments; L is the message, the elements of which need to be embedded

in the video container; K_{hid} is the steganographic key. In this case, it is necessary to ensure an increase in the steganographic capacity \hat{C}_{hid} , i.e.

$$\hat{C}_{hid} > \hat{C}_{hid,exist},$$

under conditions of exclusion of loss of integrity

$$PSNR_s \geq PSNR_{s,nes},$$

and prompt delivery

$$t_{tr,hid} \rightarrow t_{tr},$$

steganographic images using wireless information and communication systems.

The following notations are adopted here: $\hat{C}_{hid,exist}$ – steganographic capacity of existing methods; $PSNR_{s,nes}$, $PSNR_s$ – are, respectively, the required and real level of integrity of compactly represented video data with embedded information in terms of the peak signal-to-noise ratio; t_{tr} , $t_{tr,hid}$ – time delays for the transmission of compressed video data and compressed video data with embedded information, respectively.

To assess the effectiveness of the devised method, modeling was carried out in the form of a full-scale experiment. For this purpose, a software prototype was developed in the Kotlin Native programming language environment. At the same time, additional third-party libraries are not required for the correct operation of the programmed prototype. The comprehensive software IntelliJ idea IDE for Mac book air based on the m1 chip was used. No additional requirements are imposed on personal computing equipment from a performance standpoint.

To assess the effectiveness of the complex steganographic embedding method, video images were used with their preliminary classification into three types. The type of video image is determined by the saturation of segments with complex (informative) structural content. Video images of three classes were used for experiments. In each class, the number of video images was selected at least 100. Video images were selected from the recommended international video image databases tid2013. The reliability of the obtained results is confirmed by quantitative assessments of test video images with embedded information in terms of peak signal-to-noise ratio, compression level, steganographic capacity; experimental evaluation of the extraction of embedded information without loss of integrity.

5. Results of research on devising a method for complex steganographic information embedding

5.1. Development of an approach for devising a method for steganographic information hiding in the compression process based on taking into account a complex of dependence types

To substantiate the direction of building a steganographic method, it is necessary to take into account the possibilities of using a complex of different approaches to information embedding in the process of transforming a VC container during compression. In the general case, the implementation of steganographic transformation methods is determined by the following:

- the principles of steganographic information embedding;
- the functional conditions under which information hiding is carried out according to the selected method.

Accordingly, the approach to implementing steganographic information embedding is proposed to be built on the following conceptual aspects:

- use the principle of information hiding at different stages of the compression process;
- apply different functional conditions for information hiding.

The basic standardized platform for video compression is JPEG technology [16]. A sequence of transformations with an initial segment (video data array) is used. At each of these stages, the features of the content of the segments are taken into account according to psychovisual, structural, and statistical properties. At the same time, the detection of psychovisual features and the reduction of the amount of corresponding redundancy are carried out at different stages [17]. In general, the following stages can be distinguished here:

- 1) transformation of the components of the video image color description model;
- 2) reformatting the macrospace of the segments of the components of the brightness-time description of video images;
- 3) discrete cosine transform (DCT) of segments;
- 4) quantization of the spectral description (transformants) of segments.

The first component of complex steganographic transformations – LSB-embedding of information – is implemented for the quantized space of the transformants of the VC container. After that, processing is carried out taking into account dependences of non-psychovisual origin. Therefore, an option for implementing additional information embedding is the segment description spaces preceding the DCT stage.

For these formats of description of the VC container, a possible approach is to use steganographic transformations under the functional condition of indirect embedding [18].

At the same time, such methods have the disadvantage of being limited in the amount of steganographic capacity while maintaining the required level of integrity of the stego-container. On the contrary, increasing the steganographic capacity (the amount of embedded data) is accompanied by the following:

- a reduction in the amount of psychovisual redundancy, which in turn is used to embed information using LSB methods;
- introducing losses in the semantic integrity of stego-containers.

The main reason for such shortcomings is the lack of a mathematical description of the dependences between the psychovisual features of different stages of the VP-container transformation in the compression process [19].

Accordingly, this limits the possibility of joint management of the processes of steganographic information embedding and reducing the amount of redundancy of psychovisual origin at different stages of compression.

Therefore, to design an additional component of a complex steganographic system, it is proposed to embed information based on establishing and reducing the amount of redundancy of structural origin. At the same time, to exclude the destructive influence on LSB-embedding, it is necessary to implement such a process for the stages of post-quantization of the transform.

In this case, the steganographic components of the complex system will embed information taking into account dependences in the structural-psychovisual space. This creates an opportunity to unload the LSB-embedding process by additional application of the steganographic method in

the feature space, which is not associated with psychovisual dependences.

Therefore, it is necessary to devise a method for complex steganographic information embedding based on additional consideration of structural dependences in the process of processing the VC container taking into account pre-hidden information in the spectrally modified space.

This approach has the following properties regarding use for unmanned systems:

1) additional consideration of structural-positional properties involves the use of the number of typical arithmetic operations, which has a linear dependence on the volume of embedded information. Embedding is carried out in the compression process independently of the process of LSB-hiding information in the spectral space. This makes it possible to implement the process of parallel (simultaneous) information embedding using a complex of various steganographic transformations. Hence, the increase in the complexity of the frill process will be limited. This creates an opportunity to use the proposed approach for airborne systems;

2) the loss of the compression level from the information hiding process is reduced. Notably, additional consideration of structural-positional dependences creates a condition for reducing the bit volume of stego-containers. This is especially true for processing video images with a sufficient level of information content. This makes it possible to reduce the requirements for the speed of data transmission from unmanned systems. Accordingly, a condition is created for the use of PROF technologies (pseudo-reconfiguration of the operating frequency). This technology creates an opportunity for transmitting information from unmanned systems under the influence of electronic warfare agents.

We shall devise a method for steganographic information hiding in the compression process based on taking into account a complex of types of dependences of different origins. To implement steganographic transformations in the structural space, it is proposed to use coding systems in a positional basis (P-basis).

The essence of the P-basis coding method concerns the following stages of processing VC containers with message embedding:

1. Formation of the positional number \hat{S}_j for the VC container $\hat{S}_{t,g}$ in the P-basis W_j with the formation of quantitative features according to the detected dependences by the range of the intervals of their values in the spectral space, taking into account that the VC container has embedded information at the previous stage in the LSB region.

According to the above, a transitional format \hat{S}_j is formed. It depends on the presence of embedded information in the LSB region, which is denoted by the sign b . In the following, we shall denote such containers $\hat{S}_j = S(b)_j$.

Then the first stage of embedding in the P-basis is implemented based on the expression

$$\begin{aligned} r_{i,j} &= \min\left(\max\{S(\beta)_j\}; \delta_i\right) + 1 = \\ &= \min\left(\max\{Y(\alpha; \beta)_j\}; \delta_i\right) + 1, j = \overline{1, m}. \end{aligned} \quad (1)$$

Here d_i is the value of the refinement of the OHR value taking into account:

- structural dependences on the elements of the i -th row;
- the presence of influence on the values of the elements of the VC-container from the process of embedding information in the LSB-area.

The sign b takes the following values: “0” – in the absence of prior embedding of information in the LSB-area; “1” – if the VC-container already contains hidden information, which is added in the previous step using the LSB method.

The general process of transforming information components for the stegano-transformation component in a positional basis is shown in Fig. 1.

2. Adding the bit l_x of confidential information L is carried out in accordance with the features of detecting structural dependences and constructing the basis W_j . The process of steganographic transformations includes:

1) selecting the $r_{i,j}$ value of OHR of the P-basis for further modification. Such modification is carried out under the conditions of localization of the impact on the compression level. For this purpose, it is ensured that such OHRs are selected, the change of the values of which will not lead to the appearance of steganographic redundancy;

2) steganographic embedding of the bit l_x of the confidential message by proportionally changing the values of the selected value $r_{i,j}$ of OHR of the positional basis. Accordingly, a modified OHR value $r'_{i,j}$ is formed here. Such a transformation is implemented by the expression

$$r'_{i,j} = \min\left(\max\{S(\beta)_j\}; \delta_i\right) + \theta | \theta = 1 + \text{sign}(\lambda_\xi). \quad (2)$$

Further, the stages associated with the organization of compression of stegano-containers in the “APCH – NRV basis” system are performed. For this purpose, the following two stages are implemented:

1. Code formation N'_j in the modified P-basis Ω'_j . In this case, the code value depends on the characteristics of the structural dependences of the stegano-container and the modified P-basis. Such features affect the determination of weight coefficients $W'(\sigma=0)_{i,j}$ of $\hat{s}_{i,j}$ elements in the stegano-container sequences S'_j . For this purpose, the functionality $f_{wc}(\Omega'_j; r'_{i,j} | \sigma=0)$ is used. Then to calculate the N'_j value, we shall have the following relation

$$N'_j = \sum_{i=1}^m s_{i,j} \cdot f_{wc}(\Omega'_j; r'_{i,j} | \sigma=0). \quad (3)$$

2. Finally, a compact description format is formed for data transmission from onboard systems. This format is based on E_j codograms. They are formed by two components: code-information (contains information about the N'_j code value); positional-basis (contains information about the modified P-basis Ω'_j).

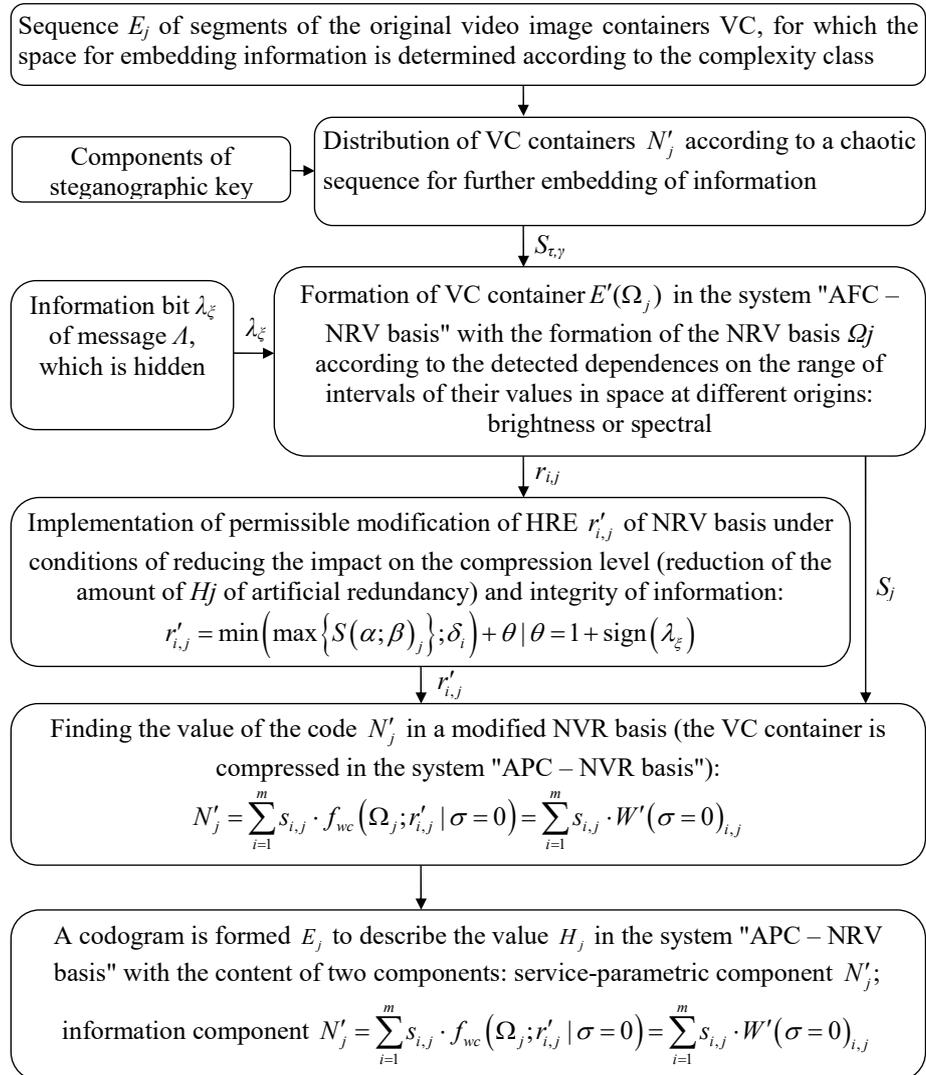


Fig. 1. Scheme of steganographic information embedding based on functional transformations with permissible modification of the positional basis

The implementation of the reverse steganographic transformation is based on the following rule

$$\lambda'_s = r'_{i,j} - \min\left(\max\{S'_j\}; \delta_s\right) + 1. \quad (4)$$

Thus, the devised method makes it possible to embed a message bit in the process of reducing the bit volume of the VC-container by modifying the value of the OPH in the P-basis under the condition of the presence of LSB-embedded information at the previous stage. The reverse steganographic transformation involves a two-aspect principle depending on the access authorization mode without affecting the integrity of the hidden information of the first LSB-stage.

The implementation of the specified approach has the following features:

1. The first feature of the steganographic system in the P-basis concerns the ability to take into account the dependences that are used in the process of reducing the bit volume on the description of the elements of the adaptive position number (APN). In this case, unlike existing approaches to information embedding, steganographic transformations do not change the nature of the dependences that are established for VC-containers. That is, modifying the OPF of individual

elements of the VC-container in the P-basis will not affect the change in the nature of the dependences (the range of the interval of values of the VC-container elements). In some cases, embedding a message bit may result in a slight change in the OPF value. However, the reduction in compression will be insignificant.

2. The second feature of the constructed functional transformations concerns the presence of the following properties:

- a change (modification) in a limited range of values of the VC-container does not significantly affect the meta-description of the structural dependences underlying the construction of the P-basis;
- information embedding is not accompanied by a change in psychovisual dependences for the VC-container, and therefore does not affect the processes of reducing the amount of psychovisual redundancy;
- the transformation of the VC-container elements in the P-basis is carried out without losing their integrity.

The specified properties provide the potential for using steganographic transformations in the P-basis as components for building a complex stegano-system, which will have the concept of multi-hierarchical information embedding.

Accordingly, the general structural and functional scheme of the method for complex steganographic embedding in the structural-psychovisual space is shown in Fig. 2.

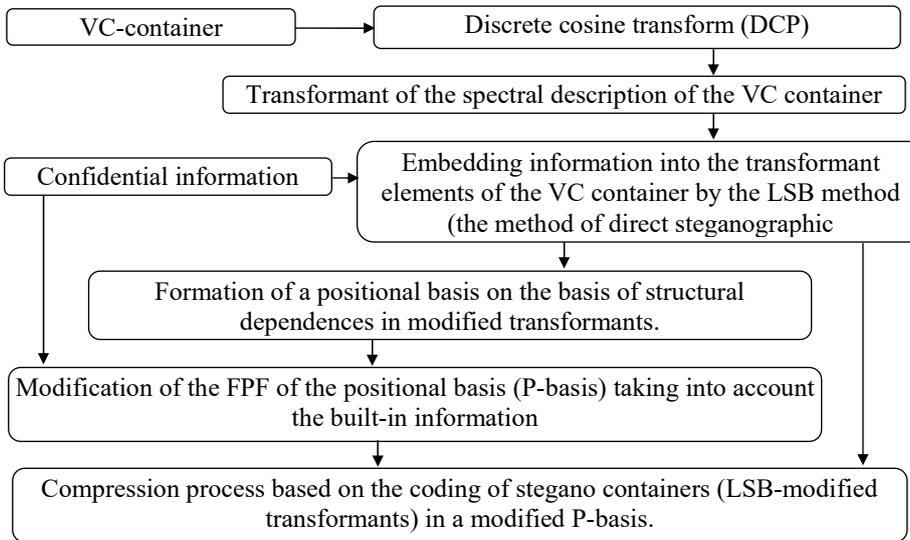


Fig. 2. Structural and functional diagram of the method for complex steganographic information embedding

In this case, information embedding can be carried out in the syntactic format of the VC-container at the stages of spectral processing in the presence of embedded information at the previous stages. Here it is possible to apply the method of direct embedding of information into the elements of VC-containers by changing the values of individual elements. For example, changing the values of the binary description elements that have the least impact on the quality of visual perception of the VC-container. This can be implemented using the LSB-embedding technique.

Thus, a new approach to steganographic information embedding has been devised, which expands the package of existing methods for information hiding.

5. 2. Evaluating the effectiveness of the method for complex steganographic embedding in comparison with existing ones

The effectiveness of the devised method of steganographic transformations will be assessed according to the following indicators:

1. Steganographic capacity (amount of embedded information).
2. Semantic integrity of the stegano-container. This value affects the determination of the quality of the recovered VC containers; the level of integrity of the confidential information that is extracted on the receiving side.

For this purpose, the mean square indicators are used: the level σ_s of the mean square deviation between the VC container before and after information embedding; the $PSNR_s$ level of the peak signal-to-noise ratio. These indicators are found, respectively, from the following formulas:

$$\sigma_s = \left(\frac{1}{Q_{row} \cdot Q_{col}} \cdot \sum_{i=1}^{Q_{row}} \sum_{j=1}^{Q_{col}} (x_{i,j} - x_{i,j}^{(rec)})^2 \right)^{1/2},$$

$$PSNR_s = 20 \lg \frac{x_{max}}{\sigma_s} \text{ (dB)}. \tag{5}$$

Here, $x_{i,j}$, $x_{i,j}^{(rec)}$ are the pixel values at position (i, j) in the original and restored VC containers with embedded information, respectively; x_{max} is the maximum pixel value.

Accordingly, if the value of n_{pix} is known, then $x_{max} = 2^{n_{pix}}$. For example, for $n_{pix} = 8$, $x_{max} = 256$.

The $PSNR_s$ metric determines the level of concealment of the fact of the presence of embedded information in the video image. Sometimes this level is interpreted as the visual stability of the steganographic system against unauthorized steganographic analysis.

Below, we consider the assessment of the steganographic capacity C_{hid} for the devised method of complex steganographic transformations (CST). The C_{hid} value is determined based on the ratio of volume V_{hid} of the actually embedded information to the video container image with volume V_{vcn} taking into account all components of its color model, i.e.

$$C_{hid} = \frac{V_{hid}}{V_{vcn}}.$$

The C_{hid} percentage value of the steganographic capacity of the system (SEC) is estimated based on the following expression

$$C_{hid} = \frac{V_{hid}}{V_{vcn}} \cdot 100\%. \tag{6}$$

For the devised method of CHS, information embedding is carried out independently at two stages of the process of

converting VC containers. Let us denote the number of bits hidden at two stages as $V_{hid}^{(1)}$ – the number of bits embedded in the spectral space by the LSB method; $V_{hid}^{(2)}$ – the number of bits embedded based on the modification of the P-basis in the process of encoding the VC container. Accordingly, the expression for the C_{hid} value will have two components

$$C_{hid} = \left(\frac{V_{hid}^{(1)} + V_{hid}^{(2)}}{V_{ven}} \right) \cdot 100\% = \frac{V_{hid}^{(1)}}{V_{ven}} \cdot 100\% + \frac{V_{hid}^{(2)}}{V_{ven}} \cdot 100\% = C_{hid}^{(1)} + C_{hid}^{(2)}$$

In this expression, the $C_{hid}^{(i)} = \frac{V_{hid}^{(i)}}{V_{ven}} \cdot 100\%$ value determines the increase in steganographic capacity for the i -th approach to embedding.

Taking into account the features of the devised CHS method, the $C_{hid}^{(2)}$ value determines the increase in SCS by applying additional embedding for the P-basis. In this case, such a value also means a gain in the value of the steganographic capacity of the devised method relative to the existing ones. Here it is assumed that one of the existing methods (IMS) of the LSB embedding class in the spectral space region is used to implement the first stage of information embedding. Variants of implementing such methods are reported in [7–9].

Further, the steganographic capacity $\hat{C}_{hid}^{(2)}$ for greater consistency with the pixel structure of video images will be determined in terms of bits/pixel. The corresponding dependence of the $\hat{C}_{hid}^{(2)}$ value in terms of bits/pixel on the sizes ($m \times m$) of VC containers (video image segments) is given in Fig. 3. From the analysis of the diagrams, it follows that the increase in the SCS for the devised method of CHS relative to the existing ones is on average 2–6.5%. Such an increase means that using the devised method of complex steganographic transformations, conditions are created for increasing the bit volume of embedded data. Such properties of the CHS method are formed by using the developed steganographic transformations in the P-basis based on taking into account structural dependences. This is estimated by the $V_{hid}^{(2)}$ value. The dependence of the $V_{hid}^{(2)}$ value on the size $Q_{row} \times Q_{col}$ of the video image (the number of VC containers) is given in Table 1.

In the process of calculations, it was taken into account that the video image consists of three components according to the color model of digital description. From the analysis of the data in Table 1, we can conclude that based on the use of the structural component of the complex steganographic embedding method, additional hiding of an average of 100 Kbit to 2.4 Mbit of information is achieved, depending on the size of the video images, compared to existing ones.

Table 1

Dependence of the $V_{hid}^{(2)}$ value on $Q_{row} \times Q_{col}$ for the devised CHS method

Size $Q_{row} \times Q_{col}$	$m = 8$	$m = 4$
Full HD (1080p) 1920 × 1080	97 Kbit	388 Kbit
4K UHD 4128 × 3096	600 Kbit	2,4 Mbit

In this case, video images of the formats that are most often used in practice are selected. Accordingly, it can be indicated that under certain conditions, an opportunity is created for additional hiding of the bit volume that corresponds

to the bit volume of color components of the CIF format video image (709 × 399).

The comparative dependence of the total steganographic capacity \hat{C}_{hid} of the devised CHS method with existing ones (IMS) on the semantic integrity indicator $PSNR_s$ is shown in Fig. 4. In this case, the information embedding mode was set based on the calculation of ensuring the level of $PSNR_s$ integrity within the permissible $PSNR_{s,nes}$ values. The compression ratio of stegano-containers under the conditions of their average degree of informativeness was chosen as given at level 8. Such a compression level was provided for existing and devised methods. The $PSNR_{s,nes}$ threshold values depend on the level of semantic complexity of VC containers. The size of the VC container was chosen at $m = 4$.

From our analysis of the diagrams in Fig. 4, it can be concluded that an increase in steganographic capacity is achieved for VC containers of different complexity while ensuring the integrity level at the required level. In this case, it is necessary to take into account the peculiarity of the devised CHS method, namely that distortions are not introduced at the second stage of steganographic information embedding.

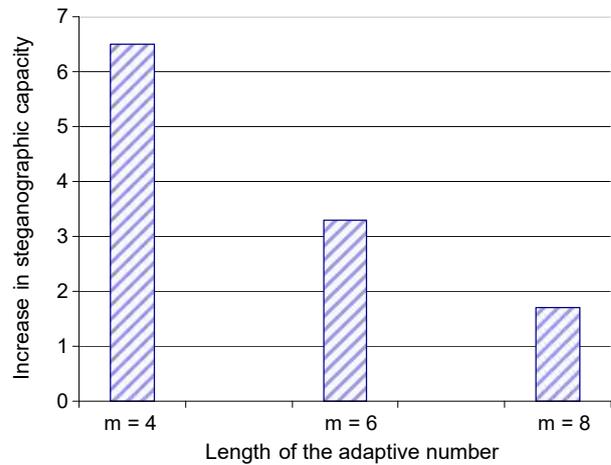


Fig. 3. Diagram of the increase in steganographic capacity for the devised method relative to existing ones depending on the length of the adaptive number

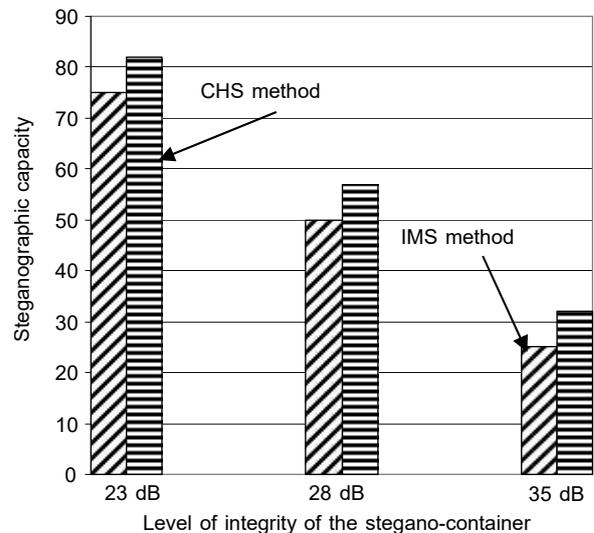


Fig. 4. Dependence of steganographic capacity on the level of integrity of the stegano-container for different methods of steganographic information embedding

Therefore, the influence on the level of semantic integrity of the stegano-container is carried out at the stage of embedding information using LSB methods.

6. Discussion of results based on steganographic transformations effectiveness

A method for complex steganographic information embedding has been devised, taking into account the structural and psychovisual dependences of video containers, based on hiding information in the components of the positional basis, which is formed for the modified stegano-spectral space (Fig. 2). Information embedding for the devised method is carried out at different stages of video container compression with the involvement of the following complex of steganographic transformations:

- information embedding in the spectral syntactic description of the video container by modifying the components of the discrete cosine transform according to the rules of the LSB approach;
- information embedding by admissible modification of the positional basis, which is built on the basis of detecting structural features in the spectrally modified space (stegano-spectral space) (Fig. 1).

Information embedding is carried out in the process of video container compression. The first stage of data hiding is organized in the spectral space. It is applied after the stage of performing the discrete cosine transformation of video fragments and quantization of spectral arrays (transform). This compression stage is the last transformation for which the proportion of psychovisual redundancy is reduced and distortions may be introduced. The post-stages of the compression process do not involve the introduction of distortions. This necessitates the application of the first stage of hiding according to the LSB rules in the quantized spectral space. The implementation of such an approach can be organized using existing steganographic methods for LSB embedding. For example, such methods are considered in [7–10]. At the same time, the specified steganographic transformations are accompanied by the introduction of distortions in video containers; changing the models of statistical dependences and partial destruction of structural dependences of the “series of zero components” type. It is these dependences that are used for further compression of video data for existing platforms. Examples of such compression platforms are given in [3, 14, 16, 17]. Hence, this leads to losses in the level of compression of video data in the presence of hidden information.

Unlike existing platforms, the devised method for compression of spectrally quantized arrays is based on adaptive positional coding in a non-equilibrium basis (Fig. 1). In this case, the reduction of the amount of redundancy is achieved by identifying and taking into account structural-positional dependences. For this purpose, the intervals of change of the values of the components of the spectral space are determined using expression (1). According to expression (3), a slight change in the values of the elements does not affect the increase in the code value, which almost eliminates the influence of quilting transformations on the loss of the compression level. At the same time, such coding is carried out without introducing information losses. These properties allow compression of spectral arrays in the presence of embedded information. This reduces the loss of compression

level and eliminates cases of loss of integrity of hidden information; introduction of additional distortions into VC containers (Fig. 3).

The second stage of complex steganographic embedding for the devised method, unlike the existing ones, is organized by admissible modification of the components of the adaptive unbalanced P-basis. For this purpose, expression (2) is used. According to this expression, the modification of the P-basis components is carried out taking into account the value of the binary element of the message being embedded. In this case, an admissible modification is considered to be one that makes it possible to avoid loss of information integrity. For this purpose, in the devised method, the modification of the P-basis component is carried out for the senior element of APN. At the same time, the masking of such changes is due to the sliding length of position intervals for spectral arrays under the conditions of their quantization. Modification of the P-basis component of the senior element makes it possible to exclude the influence on the process of forming the code value (3). This is due to the fact that such a P-basis component is not used to form the weight of the elements of the sequence being encoded. Hence, the influence of the specified modifications on the code value (Fig. 1) and the loss of the compression level is excluded. So, the second stage of complex embedding for the devised method is carried out on the basis of taking into account structural-positional dependences with the exclusion of losses in the level of compression and integrity of information, including pre-embedded at the previous stage of messages; VC-container.

Extraction of hidden information is ensured without loss of integrity. For this purpose, relation (4) is used. Extraction of hidden information elements is carried out by comparing the modified value of the P-basis component with the actual value, which is formed on the basis of lossless restoration of the spectral array elements.

Thus, for the devised method, compared to the existing ones reported in [7–10] and related to the use of LSB embedding, an increase in the level of steganographic capacity without loss of integrity and the level of integrity is achieved. This is demonstrated in the diagrams of Fig. 3 and the data in Table 1. This becomes possible due to the use of the second stage of information hiding based on taking into account structural-positional type dependences without loss of information and excluding the impact on the compression level.

The exclusion of additional losses of integrity of stegano-containers in terms of the peak signal-to-noise ratio (expression (5)) is demonstrated in the diagrams of Fig. 4. It is shown that for a given level of compression and integrity, an advantage in steganographic capacity is provided.

At the same time, the implementation of the second stage of steganographic transformations for the devised method involves the use of the number of typical arithmetic operations in linear dependence on the volume of hidden information with the possibility of simultaneous embedding with the first stage. That is, for the devised method, there is a possibility of embedding information simultaneously in two stages. This reduces the requirements for the complexity of the computational process and restrictions on delays in the processing process. Accordingly, the possibility of using the devised method of complex information embedding for on-board technologies is ensured.

Thus, the use of the second stage of information hiding in combination with the previous stage of LSB-embedding makes it possible:

- to increase the level of steganographic capacity (Fig. 3 and Table 1) without introducing losses in the compression level and preserving the level of information integrity;
- to reduce the level of information integrity losses under the conditions of a given steganographic capacity by reducing the number of distortions for the LSB embedding stage;
- to increase the compression level by additionally eliminating the number of redundancy taking into account structural-combinatorial type dependences.

From this it can be stated that the devised method makes it possible to solve the scientific problem of this study.

The results of evaluating the effectiveness of the devised method for complex steganographic embedding in comparison with existing ones are illustrated in the diagrams of Fig. 3, 4, as well as in Table 1.

In the process of conducting experiments, video images from international video frame databases recommended for processing are used. In this case, video images with different levels of complexity of structural and semantic content are selected. For experimental processing, 100 representatives of test video frames of three types were selected depending on the complexity of the semantic content. For this purpose, the recommended base of test video frames *tid 2013*, which is considered in [20], was used.

Fig. 3 shows a diagram of the dependence of the increase in steganographic capacity on the size of the adaptive position number for the devised method of complex steganographic embedding due to the use of the second stage of information hiding. Such an increase actually indicates the amount of additionally embedded information relative to existing methods with LSB embedding, which are considered in [7–10]. Therefore, the increase value can be used as an assessment of the advantage of the devised method over existing ones in terms of steganographic capacity. In this case, the conditions are provided: lossless extraction of hidden information; masking the fact of the presence of hidden information in video containers. From the above estimates, it can be stated that for the devised method, when using a 4K UHD (4128 × 3096) video image as a container, additional information embedding of 2.4 Mbit is provided relative to existing approaches. This is given in Table 1.

Fig. 4 shows diagrams of comparative assessment of the total steganographic capacity at two stages of the devised method and existing methods with LSB embedding. Obtaining such estimates is carried out for the compression ratio specified at level 8 depending on the level of integrity of video images with embedded information (stego-containers) in terms of the peak signal-to-noise ratio. Estimates were obtained as average values for different types of video images. The number of video images was 320. Analysis of the diagrams indicates the achievement of an increase in the level of steganographic capacity for the devised method by 7% relative to existing methods that use the LSB embedding technique, under the conditions of the required level of integrity of stego-containers. The required level of integrity in terms of the peak signal-to-noise ratio was selected depending on the level of complexity of video segments, namely for:

- low informative video segments not less than 23 dB;
- medium informative video segments not less than 28 dB;
- for informative video segments not less than 35 dB.

The main differences of the devised method are as follows:

1) information embedding is carried out in the process of modifying the P-basis values taking into account: detection of structural dependences in the spectrally modified spaces of

the VC-container; conditions for the admissibility of correction of the P-basis values to exclude integrity losses;

2) use of a sequential set of steganographic transformations in independent spaces to detect dependences that are used in the process of information embedding; information embedding is carried out in the structural-spectral space taking into account its modification by the youngest bits;

3) for compression of quilted containers under the information loss exclusion mode, adaptive positional coding in a non-equilibrium basis is used and additional elimination of the amount of redundancy is provided taking into account dependences of structural-combinatorial origin.

The limitation of our research is its focus on the use of static video containers without taking into account the presence of noise and the use of spectral space regions for information embedding. The disadvantage of the study is the unresolved issue of taking into account the presence of natural noise for video images, which is due to the peculiarities of their registration process, and the choice of a cryptographic method for preliminary protection of messages that are embedded in the video container.

Further development of this research concerns four areas. The first direction is the scaling of the devised method under the conditions of using dynamic video containers. This will provide an opportunity to increase the amount of information that is hidden by taking into account dependences in the video frame stream. The second direction is the scaling of the devised method to the conditions of information hiding in the field of wavelet transforms. This will provide an opportunity to integrate the devised method into other compression formats, for example, JPEG 2000, JPEG-XL. The third direction is the development of a scheme for adapting the devised method to the conditions of preliminary cryptographic encryption of data that is being hidden. This will ensure an increase in the level of information protection. The fourth direction is to take into account the presence of noise in video image registration. Taking into account the models of such noise will provide an opportunity to increase the amount of embedded information while masking the fact of such transformations.

7. Conclusions

1. The approach and architecture of the method for complex steganographic embedding based on information hiding taking into account the structural-psychovisual dependences of VC containers have been developed. The basic components of the method are:

- the process of embedding information in the spectral description of the VC container by modifying the components of the DCP transform according to the rules of the LSB method;
- the process of embedding information by admissible modification of the positional basis, which is built on the basis of detecting structural features in the spectrally modified space (stego-spectral space).

The main differences of the method are as follows:

- the use of a complex of steganographic transformations in independent spaces to detect dependences that are used in the compression process;
- information embedding is carried out in the process of modifying the P-basis values taking into account: detecting structural dependences in the spectrally modified spaces of the VC container; conditions for admissibility of correction of the P-basis values to exclude integrity losses.

This makes it possible to increase the level of steganographic capacity without losing the compression level and maintaining a given level of information integrity.

2. According to the results of experimental evaluation of the effectiveness of the devised method for complex steganographic embedding in comparison with existing ones, it provides:

– an increase in the level of steganographic capacity by an average of 2–6.5% without introducing losses in the compression level and maintaining the required level of information integrity (28–35 dB). This, under the conditions of using common video image formats, allows for additional embedding on average from 100 Kbit to 2.4 Mbit of information depending on the size of the video images;

– a reduction in the level of information integrity losses under the conditions of a given steganographic capacity by reducing the number of distortions for the LSB embedding stage. The required level of information embedding can be achieved for an integrity level at a peak signal-to-noise ratio of 28–35 dB. This creates conditions for increasing the compression level or steganographic capacity.

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, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Volodymyr Barannik: Conceptualization, Data curation, Methodology, Project administration, Supervision, Validation, Writing – original draft; **Dmitry Barannik:** Investigation, Methodology, Software development; **Mykhailo Babenko:** Data curation, Methodology, Validation, Formal analysis; **Rodion Prokopenko:** Data curation, Investigation; **Oleksandr Akimov:** Validation, Visualization; **Nina Petrukha:** Resources (provision of video materials for processing), Visualization.

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