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METHOD OF COMPRESSION AND ENSURING THE FIDELITY OF VIDEO IMAGES IN INFOCOMMUNICATION NETWORKS

Subject *research in the article is the methods of compressing video images under conditions of ensuring the desired level of their* fidelity *in the delivery process using infocommunication networks. The* ***goal*** *is to develop methods of encoding video images for increasing the level of their compression in the conditions of ensuring required reliability.* ***Task:*** *to substantiate the approach regarding the structural clusterization of transformed video segments in the conditions of preserving their reliability; to develop a method of structural and statistical coding of transformants in the spectral-cluster space; conduct a comparative evaluation of the effectiveness of various methods of encoding video segments.* ***The methods*** *used: mathematical models for estimating the amount of statistical and structural redundancy in the clustered spectral space of video segments; methods of statistical coding. The following* ***results*** *have been obtained. The potential effectiveness of representing a transformant in clustered space by the number of series of units in binary description of their components has been substantiated. A method of structural-statistical coding in the spectral-cluster space has been created. The basic component of this technological approach is the evaluation of the estimates regarding the potential ability to eliminate various types of redundancy in the current cluster. Here, the amount of redundancy is reduced considering the statistical and structural features of the cluster. The comparative evaluation revealed the advantages of the created method over coding methods in standardized platforms. The advantage is achieved in terms of the peak signal-to-noise ratio by at least 30%. and in terms of a compression ratio by an average of 12 %.* ***Conclusions.*** *The scientific novelty of the obtained results is as follows: for the first time, a method of structural-statistical coding of video segments in spectral space based on their clusterization has been created. The differences of the method lie in the fact that the component of the transformant is simultaneously interpreted as an element of the statistical and combinatorial cluster space; the potential capabilities of eliminating various types of redundancy in the clustered transformant are considered. This provides an increase in the level of compression of video images for a given level of reliability.*

Keywords: *aerial photographs; video data compression; information reliability; structural clustering; coding in spectral-cluster space; structural-statistical redundancy.*

Introduction

Formulation of the problem. The organization of information support for critical infrastructure (CI) management systems in modern conditions is characterized by the following aspects :

1) the use of video information resources is widely spread for the analysis of the state of the objects of monitoring. Video images and dynamic video data are used here [1];

2) application of mobile remote sensors for collection and registration of video information, including the use of unmanned aerial vehicles [2];

3) application of wireless infocommunication networks (ICN) as well as on-board platforms [3].

Accordingly, the requirements are increasing for:

a) completeness of video information resources [4]. The number of pixels in a video frame has increased by an average of 16 times over the past few years;

b) timeliness and fidelity of video information [5]. Timeliness is defined by the total time delays for processing and transmitting the information. Fidelity is defined by the level of correspondence between the restored and original video images.

Hence, the question regarding ensuring the necessary quality indicators for ensuring a remote video service arises [6]. Here, it is necessary to take into account the following peculiarities:

- the process of video information analysis in CI systems;

- significant criticality of video information regarding the impact on the decision-making process

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and the level of consequences in case of its disruption. There are recommendations regarding the quality of providing video information in aerial monitoring systems. They are determined by the standards STANAG 4671:2009 [7], STANAG 7023:2009 [8]. Given that, the following requirements come into force:

1) regarding the determination of the fidelity of the received video information. A hierarchy of levels has been established for the quantification of fidelity, viz:

- for the highest criticality of information, it is necessary to ensure a mode of processing without loss of information. In this case, the number of distorted pixels or the mean square deviation should be zero;

- for the least critical information, pixel distortions of video frames are allowed. The admissible level of such distortions according to the peak signal-to-noise ratio (PSNR) should be at least 25-33 dB. It depends on the purpose of the video frames;

2) regarding time delays in the process of processing and transmitting video frames. Such an indicator depending on the criticality and time of relevance (aging) of the information should be at the level of several 10 ms to several seconds.

The abobe-mentioned trends require the use of ICN with the required level of information transmission speed. At the same time, there is an imbalance for the systems that provide remote video services using wireless ICN on aviation platforms. It refers to the fact that exists:

- on the one hand, lagging of the rate of increase in ICN productivity in terms of data transfer rate;

- on the other hand, the growth rate of the bit intensity of video information streams.

Such imbalance leads to the occurrence of significant time delays in the process of video information delivery. It results in the losses of [9]:

- the relevance (adequacy) of video information regarding the current state of the objects of monitoring;

- the fidelity of video information. This is due to the fact that in the case of a limited connection time, a video frame or a group of them will not be received in full.

These destructions are the cause of the disruption of the decision-making process in critical infrastructure systems.

Therefore, there is an urgent need to solve the ***scientific and applied problem*** of improving the quality of remote video services using wireless infocommunication networks.

State of the art. To solve this problem, a set of technological solutions is used.

The main components here are as follows:

1) increasing the bandwidth of wireless infocommunication networks [10];

2) the application of technologies for reducing bit intensity of a video stream [11 – 19].

Let's consider the first direction. The destabilizing factors inherent in wireless information transmission systems should be taken into account, namely:

- the presence of a whole spectrum of interference, electromagnetic noise, and interference of artificial origin;

- mutual electromagnetic interference of devices of the same channel (or neighboring frequencies);

- signal attenuation in the environment.

All this leads to a potential increase in the probability of errors in the codegrams that are transmitted with the use of wireless infocommunication networks.

On the other hand, there are requirements for information transmission networks in critical infrastructure systems. They relate to the fact that [20]:

- the probability $P(e)$ of a bit error in the case of transmission of a general information stream should not exceed the level of 10^{-4} , i.e. $P(e) \le 10^{-4}$;

- in the case of transmission of a video information stream, it is necessary to ensure that: the number ν'_{px} of distorted pixels is no more than 3…5 %; the number ν'_{pac} of lost packets is no more than 3 %.

To ensure the above requirements for on-board ICN, interference-resistant coding methods are used. The most widespread are parity check codes, Bowes-Choudhury-Hockingham (BCH) codes [21], Reed-Solomon codes [22].

The use of these code systems creates a possibility for detecting and correcting bit errors. Such errors occur in codegrams during their transmission through communication channels. This possibility is achieved due to the additional involvement of redundant binary digits. This increases the original bitrate V_{beg} of video frames by an average of 1.5 to 3 times. Accordingly, time t_{tr} delays in the process of their transmission by infocommunication networks are increasing. The losses regarding the efficiency of information can reach 10 times.

Therefore, it can be asserted that the application of interference-resistant codes leads to an increase in the information load on:

- on-board means of video information recording;
- computing devices;
- information transmission technologies.

Risks arise regarding the loss of fidelity and relevance of video information in case of overflow of on-board media and a limited communication session.

Let's consider the second direction. The localization of the destructive influence of channel errors on the fidelity of restored video images concerns the consideration of psychovisual features [11]. This direction is based on the fact that some distortions of individual pixels and areas of a video frame do not lead to desruption of overall visual evaluation. In this case, errors at the syntactic level of the description of a video image do not lead to a loss of fidelity at the level of its structural and semantic content [12].

At the same time, certain psychovisual features of video images are used in modern compression technologies. As a result, the bit volume of the video frame is reduced [13]. By eliminating the amount of such redundancy the greatest reduction in the bit volume of video images is achieved [14].

Hence arises the conflict between ensuring the fidelity of video images and their timely delivery. This refers to the fact that the amount of psychovisual redundancy is used for:

- localizing the destructive effect of channel errors on the fidelity of video images;
- reducing the bit volume of video images.

Therefore, the implementation of remote video services using on-board ICNs puts forward additional requirements for the technologies reducing the bit volume of video data. Thus, ***the goal of the article*** is to develop methods of encoding video images to increase the level of their compression under the conditions of ensuring the required fidelity.

Rationale of the approach for improving video compression methods under the conditions of ensuring their fidelity

To ensure a reduction in the bit intensity of video data, standardized platforms are used, namely: JPEG for encoding static video images [15]; MPEG-4, H.264/AVC, H.265/HEVC for encoding a dynamic stream of video frames [16].

At the core of such platforms is a technological solution based on the elimination of a number of psychovisual and statistical redundancies. At the same time, such processing is carried out in the frequency-spectral representation of a video segment [17].

The reduction of the amount of psychovisual redundancy is carried out on the basis of quantization of transformant components (an array of spectral coefficients). Here the features of the high-frequency components of a transformant are taken into account. Such components mostly contain information about small details of a video segment [18].

Statistical redundancy in transformants is due to the presence of probabilistic features. This will be manifested in the fact that [19]:

- transformants have limited capacity (the number of components with different values);
- the law of probability distribution of the transformant components tends to be uneven.

The exclusion of the amount of redundancy occurs due to the use of statistical coding methods. The examples of such methods are various modifications of the Huffman code [23, 24] and arithmetic coding [25, 26]. To increase the compression ratio, the lengths of series of components that have zero values are additionally taken into account [27].

Such technological solutions are most effective in the case [28]:

- of encoding low-informative video images;
- when it is assumed that there are no codegrams damaged by channel interference.

On the contrary, the lowest effectiveness of the specified methods appears in the case of:

- processing sufficiently informative video images, which include aerial photographs;
- taking into account the destructive effect of channel errors.

This is due to the systemic shortcomings of standardized technological solutions. They concern the following:

1. The limited value of the compression ratio due to:

a) the reduction of psycho-visual and statistical redundancy of transformants, which is potentially reduced in the process of encoding;

b) the increase in capacity of a transformant and, the approximation of the probability distribution of components to the uniform law;

c) the increase in the degree of saturation of the video segments with small details.

The informative weight of the high-frequency components of the transformant increases. In these conditions, additional elimination of the amount of psychovisual redundancy is accompanied by:

- the significant loss of the quality of video images;
- the resolution of aerial photographs;
- the destruction of individual informative sections of a video frame.

2. The low level of stability of the decoding process of the codegrams damaged by channel errors in terms of maintaining the fidelity of video segments. Such circumstances are caused by the following vulnerabilities of standardized technologies:

- in the case of using non-uniform-prefix (NUP) codegrams, an error in one bit inevitably results in the failure to decode subsequent codegrams. An avalanche effect regarding the propagation of the channel error to the decoding process of other codegrams arises;
- the effect of error propagation is significantly enhanced in the case of forming codegrams taking into account the length of a series of zero components.

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The estimates of the negative impact of channel errors on the fidelity of video images are shown in the form of diagrams in Fig. 1. The level of fidelity of restored video images is estimated by the indicator of the peak signal/noise $PSNR_e$. The level of errors in the data transmission channels is ($P(e)=10^{-4}$ and $P(e)=10^{-5}$). The estimation is carried out without the use of interference-resistant coding.

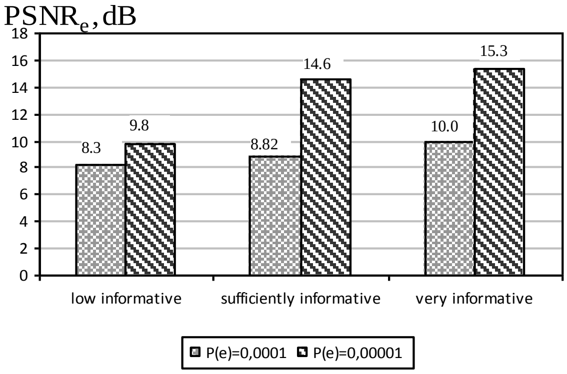

Fig. 1. Diagram of the dependence of the peak signal/noise $PSNR_e$ ratio $P(e)$ on the communication channel

The analysis of the diagrams in Fig. 1 allows us to state that the required level of $PSNR_{nes}$ is not provided in any case. A decrease in the value of $PSNR_e$ relative to the level of $PSNR_{nes}$ is observed. Depending on the informativeness of video segments, the value of $PSNR_e$, is: $3-38$ % for $P(\varepsilon)=10^{-5}$; $36-47$ % for $P(\varepsilon)=10^{-4}$.

Therefore, standardized compression technologies are not resistant to the influence of channel errors on the decoding process of damaged codegrams.

Hence it is proposed to improve standardized methods in the following directions:

1) to identify new regularities the consideration of which will create conditions for:

- additional reduction of the bit volume of video segments without introducing losses regarding the fidelity of information;
- the localization of the destructive effect of channel errors in the process of video image reconstruction;

2) to form code constructions using a mode of uniform or locally uniform code formation.

Justification of the approach to structural clusterization of transformants

It is necessary to create new coding systems that are not associated with information loss. One of the directions is the development of transformant restructuring technology. It ensures:

1) the redistribution of components in such a way that the law of distribution of probabilities of their occurrence tends to be uneven;

2) the reduction in the capacity of data sets (clusters);

3) the waiver of the prefixity of codegrams in the event of an increase in the capacity of data sets, a decrease in the probability of emerging individual components;

4) the use of uniform code constructions as well as information reference markers. Uniform codegrams of individual components serve as reference markers between the sequences of uneven codegrams;

5) the reduction of bit costs for the informative part of code structure of a transformant;

6) the stabilization of the change of probabilities for the segment transformants. Statistical models for transformants within the segment will have stationary characteristics.

A variant of the creation of the given properties lies in the transformant clusterization [29, 30].

The clusterization of transformants is ***proposed*** to be carried out in the binary space of components. The potential for additional reduction of the amount of redundancy in the binary description of transformant is created. At the same time, information loss is excluded.

The clusterization is based on the approach to partitioning the general space of bit-length binary sequences [29]. The length of binary sequences is equal to ℓ bit. Such space is determined by the set of possible ***permutations with repetition***, which are formed from ℓ-bit binary sequences. The specified binary sequences form a set $\Omega(\ell)$. Based on the definition of the set $\Omega(\ell)$, its volume $|\Omega(\ell)|$ is determined by the following formula: $|\Omega(\ell)|=2^{\ell}$. Therefore, the clusterization of a set $\Omega(\ell)$ of binary sequences is in the formation of separate subsets $\Omega(\ell;\theta)$ according to the structural feature θ. At the same time the subsets $\Omega(\ell;\theta)$ do not intersect, i.e.:

$$\Omega(\ell;\gamma)\bigcap\Omega(\ell;\chi)=\varnothing,\ \text{where}\ \gamma\neq\chi$$

$$\text{and}\ \Omega(\ell;\gamma),\ \Omega(\ell;\chi)\in\Omega(\ell).$$

The number of subsets $\Omega(\ell;\theta)$ and their volume $|\Omega(\ell;\theta)|$ depends on the choice of a specific feature θ. As such a feature θ, it is ***proposed*** to use such a structural characteristic of binary sequences as the number of series of units. This is due to the possibility of determining:

- the volume of the set of admissible binary sequences;
- the potential amount of structural redundancy that can be reduced in the coding process.

Accordingly, for the selected feature, we have the following expressions for finding quantitative parameters $|\Omega(\ell;\theta)|$, Θ of the clusterization, namely [29]:

$$|\Omega(\ell;\theta)| = \frac{(\ell+1)!}{(2\cdot\theta)!\cdot(\ell+1-2\cdot\theta)!}\;;\;\Theta = [\frac{\ell+1}{2}]+1\,.$$

Here Θ is the nominal number of values that the feature θ takes, i.e. the nominal number of subsets $\Omega(\ell;\theta)$ which is formed for the sets $\Omega(\ell)$ by the feature θ. So we have the following expression for the structure of the set $\Omega(\ell)$ by the selected feature θ:

$$\Omega(\ell) = \bigcup_{\theta=0}^{\Theta-1}\Omega(\ell;\theta) = \bigcup_{\theta=0}^{[\ell+1/2]}\Omega(\ell;\theta)\,.$$

The volume $|\Omega(\ell)|$ of the set $\Omega(\ell)$ due to the values $|\Omega(\ell;\theta)|$ of the subsets $|\Omega(\ell;\theta)|$ is represented by the following relation [29]:

$$|\Omega(\ell)| = \sum_{\theta=0}^{\Theta-1}|\Omega(\ell;\theta)| = \sum_{\theta=0}^{[\ell+1/2]}|\Omega(\ell;\theta)|\,.$$

Hence for a given ℓ between the volume $|\Omega(\ell)|$ of the general binary space $\Omega(\ell)$ and the volume $|\Omega(\ell;\theta)|$ of the subset $\Omega(\ell;\theta)$ the relation holds:

$$|\Omega(\ell;\theta)| = \frac{(\ell+1)!}{(2\cdot\theta)!\cdot(\ell+1-2\cdot\theta)!} < |\Omega(\ell)| = 2^{\ell}\,,\;\theta=\overline{0,\Theta-1}\,.$$

Accordingly, the binary sequences of the subset $\Omega(\ell;\theta)$ are ℓ-bit permutations with repetitions that contain θ of series of units.

Development of the method of structural-statistical coding of transformants in the spectral-cluster space

It is ***proposed*** to carry out the clusterization of the transformant Y_u into separate clusters $Y(\theta)_u$. The distribution of the $y_{i,j}^{(u)}$ components by clusters is carried out by determining the number θ of series of units. The value θ in the binary description $[y_{i,j}^{(u)}]_2$ of the component is found using the functional $\varphi_{clrster}([y_{i,j}^{(u)}]_2;\theta)$ [30].

The implementation of statistical coding in the ***spectral-cluster*** space has the following features [31]:

1. On the one hand, the advantages relative to the case of statistical encoding of transformants are achieved. Such advantages relate to:

1.1. Increasing the number $R(\theta)_u$ of statistical redundancy that can potentially be reduced in the process of coding the components $y(\theta;g)_{i,j}^{(u)}$ SC $Y(\theta)_u$. The increase in the level of uneven distribution of clustered components is achieved.

1.2. The creation of the conditions for reducing the length of codegrams of clustered components relative to the case of their processing as part of the entire transformant. Therefore, the components in the cluster $Y(\theta)_u$ have a higher probability than in the transformant.

The conditions are created for a syntactic description of the clustered components $y(\theta;g)_{i,j}^{(u)}$ with the codegram $c_{var}(\theta;g)_{i,j}^{(u)}$ of the shorter length $v_{var}(\theta;g)_{i,j}^{(u)}$ than the length $v_{var\,i,j}^{(u)}$ of the codegram $c_{var\,i,j}^{(u)}$. Therefore, the inequality holds $v_{var}(\theta;g)_{i,j}^{(u)} \le v_{var\,i,j}^{(u)}$. Here $c_{var\,i,j}^{(u)}$ is the codegram of the components $y(\theta;g)_{i,j}^{(u)}$ in the composition of the entire transformant.

2. On the other hand, there are still systemic shortcomings associated. They are related to the coding of transformants for sufficiently informative video images. This is manifested in the increase in the length $v_{var}(\theta;g)_{i,j}^{(u)}$ of the NP codegrams $c_{var}(\theta;g)_{i,j}^{(u)}$ in the case of an increase in the capacity $D_\theta^{(u)}$ of the SC $Y(\theta)_u$, i.e.:

$$v_{var}(\theta;g)_{i,j}^{(u)} \to v_{var\,i,j}^{(u)} \text{ or } v_{var}(\theta;g)_{i,j}^{(u)} \to \ell$$

$$\text{for } D_\theta^{(u)} \to D^{(u)}\,.$$

To eliminate the identified shortcomings, it is ***proposed*** to develop coding with additional consideration of structural properties of clusters. Accordingly, it is ***necessary*** to develop a technology for limiting the growth of the lengths of NP codegrams. For this purpose, you need to identify the cases of:

- increasing the power of cluster;

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- the approximation of the distribution of probabilities of the emergence of components in the cluster to a uniform law.

It is ***proposed*** to use the ***principle of duality*** of transformant components in the basis of such a technological mechanism. It lies in the fact that a clustered component can simultaneously be considered as:

- an element of the statistical cluster space;
- an admissible element of a structural cluster, i.e. as one of the admissible permutations with repetitions with a specified number of series of units.

Therefore, clustered components are admissible combinations of the structural cluster space according to the determined feature θ. In this case, the set of components within the SC is considered according to the structural approach.

At the same time, there are possible cases for the SC when the potential number $R_{str}(\theta)_u$ of redundancy, which is reduced taking into account structural restrictions, will exceed the number $R_{stat}(\theta)_u$ of redundancy taking into account statistical dependencies. So, the inequality holds: $R_{str}(\theta)_u \geq R_{stat}(\theta)_u$.

In this case, to further reduce the bit volume, it is necessary to code clustered components taking into account structural features of their binary description. Accordingly, it is ***proposed*** to use the property of structural clusters. It lies in the limitation of the realistic power $D_\theta^{(u)}$ for the θ-th SC by the value of the nominal power $D_{\theta,\ell}$.

That is, the inequality holds $D_\theta^{(u)} \leq D_{\theta,\ell}$. The nominal capacity $D_{\theta,\ell}$ of the SC means the maximum possible number of binary sequences $[\,y'(\theta;\, d)_{i,j}^{(u)}\,]_2$, $d = \overline{1,\, D_{\theta,\ell}}$, which:

- contain θ of a series of units;
- have such values $y'(\theta;\, d)_{i,j}^{(u)}$ of the decimal description when the condition is met:

$$[\,y'(\theta;\,\chi)_{i,j}^{(u)}\,]_2,\, [\,y'(\theta;\,\gamma)_{i,j}^{(u)}\,]_2 \in Y(\theta)_u,$$

$$\text{and } y''(\theta;\,\chi)_{i,j}^{(u)} \neq y'(\theta;\,\gamma)_{i,j}^{(u)}.$$

At the same time, under such conditions, the specified binary sequences are admissible combinations.

The entire set of such admissible ℓ-bit combinations makes a subset $\Omega(\ell;\,\theta)$. Hence the value $D_{\theta,\ell}$ is equal to the volume $|\,\Omega(\ell;\,\theta)|$ of the subset $\Omega(\ell;\,\theta)$ according to the structural feature θ. So

$$Y'(\theta)_u \in \Omega(\ell;\,\theta) \in \Omega(\ell),$$

and

$$D_\theta^{(u)} \leq D_{\theta,\ell} = |\,\Omega(\ell;\,\theta)| = \frac{(\ell+1)!}{(2\cdot\theta)!\cdot(\ell+1-2\cdot\theta)!} < 2^\ell.$$

On the other hand, it is possible to use the principle of formation of locally uniform (LU) codegrams for the admissible binary sequences $[\,y(\theta;\, g)_{i,j}^{(u)}\,]_2$ within the defined SC. The uniformity is caused by the fact that the length of the locally uniform (uniform length) codegram $v_{ufr}(\theta;\, g)_{i,j}^{(u)}$ for the binary description $[\,y(\theta;\, g)_{i,j}^{(u)}\,]_2$ of the component $y(\theta;\, g)_{i,j}^{(u)}$ is limited by the value $V_{\theta,\ell}$. Therefore, the inequality holds: $v_{ufr}(\theta;\, g)_{i,j}^{(u)} < V_{\theta,\ell}$.

The locality of this property is caused by the heterogeneity of $V_{\theta,\ell}$ values for different SCs.

The use of such a code strategy is due to the limitation of code values $E(\theta;\, g)_{i,j}^{(u)}$ of binary sequences $[\,y(\theta;\, g)_{i,j}^{(u)}\,]_2$ by the nominal power $D_{\theta,\ell}$ of the cluster. Therefore, the inequality holds:

$$E(\theta;\, g)_{i,j}^{(u)} \leq D_{\theta,\ell} - 1.$$

Indeed, the nominal power $D_{\theta,\ell}$ of the SC $Y(\theta)_u$ is the number $|\,\Omega(\ell;\,\theta)|$ of admissible binary sequences $[\,y'(\theta;\, g)_{i,j}^{(u)}\,]_2$ that have:

- different code values $E(\theta;\, g)_{i,j}^{(u)}$;
- the same number θ of series of units.

Therefore, in the event of an increase in the length $v_{var}(\theta;\, g)_{i,j}^{(u)}$ of the NP codegrams $c_{var}(\theta;\, g)_{i,j}^{(u)}$, it is suggested that the binary sequences $[\,y(\theta;\, g)_{i,j}^{(u)}\,]_2$ be coded taking into account structural features of the cluster. Accordingly, the LU codegrams $v_{ufr}(\theta;\, g)_{i,j}^{(u)}$ are formed. This will allow us to:

- limit the growth of lengths $v_{var}(\theta;\, g)_{i,j}^{(u)}$ of the NP codegram $c_{var}(\theta;\, g)_{i,j}^{(u)}$;
- create ***reference codegrams*** $c_{ufr}(\theta;\, g)_{i,j}^{(u)}$ in a general bit stream. Therefore, to localize the destructive effect of channel interference in the case of decoding the NP codegrams $c''_{var}(\theta;\, g)_{i,j}^{(u)}$ damaged by them.

Let us consider the method of encoding the binary syntactic description $[y(\theta; g)_{i,j}^{(u)}]_2$ of clustered components $y(\theta; g)_{i,j}^{(u)}$. The structural and statistical regularities $\{P'(\theta)_u; \theta\}$ of the cluster $Y(\theta)_u$ are taken into account here.

Stage 1. The first technological stage is related to the estimation of the number of redundancy in the current cluster $Y(\theta)_u$. Two approaches are used, namely the detection of:

- the probabilities $p'(\theta; d)_{i,j}^{(u)}$ of emergence of the $y'(\theta; d)_{i,j}^{(u)}$ components and realistic capacity $D_\theta^{(u)}$;

- the number of θ series of units for ℓ bit binary description $[y(\theta; g)_{i,j}^{(u)}]_2$ of the components $y(\theta; g)_{i,j}^{(u)}$.

Therefore, firstly, the estimation of the number $R_{stat}(\theta)_u$ of statistical redundancy in the $Y(\theta)_u$ SC is carried out. Such redundancy can potentially be eliminated during a coding process (formation of uneven-prefix codegrams $c_{var}(\theta; g)_{i,j}^{(u)}$). That is, the potential ability of statistical methods to eliminate the maximum number of redundancy in a cluster is established. For this purpose, the entropy $H(\theta)_u$ of the distribution $P'(\theta)_u$ of clustered components $y'(\theta; d)_{i,j}^{(u)}$ is calculated. The expression is used:

$$H(\theta)_u = -\sum_{d=1}^{D_\theta^{(u)}} p'(\theta; d)_{i,j}^{(u)} \cdot \log_2 p'(\theta; d)_{i,j}^{(u)} .$$

Secondly, the minimum number $R_{str}(\theta)_u$ of structural redundancy in the θ-th cluster is estimated. The formula is used to determine the number $|\Omega(\ell; \theta)|$ of admissible sequences $[y'(\theta; d)_{i,j}^{(u)}]_2$ in a structural set $\Omega(\ell; \theta)$ by the feature θ:

$$|\Omega(\ell; \theta)| = D_{\theta,\ell} = (\ell+1)! \,/\, ((2\cdot\theta)! \cdot (\ell+1-2\cdot\theta)!) .$$

Here $D_{\theta,\ell}$ is the number of admissible binary sequences in a structural cluster $Y(\theta)_u$ (volume of the set $\Omega(\ell; \theta)$), i.e. the number of sequences $[y'(\theta; d)_{i,j}^{(u)}]_2$ that satisfy the conditions:

- the decimal description $y'(\alpha; d)_{i,j}^{(u)}$ has different values, i.e.: $y'(\alpha; d)_{i,j}^{(u)} \neq y(\beta; \gamma)_{i,j}^{(u)}$;

- the number of series of units is equal to θ, $\alpha = \beta = \theta$, $\gamma \neq d$, $\gamma, d = \overline{1, D_{\theta,\ell}}$;

- the length $\ell(\theta; d)_{i,j}^{(u)}$ and $\ell(\theta; \gamma)_{i,j}^{(u)}$ of binary sequences $[y'(\theta; d)_{i,j}^{(u)}]_2$ and $[y'(\theta; \gamma)_{i,j}^{(u)}]_2$ are equal to the magnitude ℓ.

Hence the upper limit $V_{\theta,\ell}$ of the amount of information of a cluster structural description is calculated in the following way:

$$V_{\theta,\ell} = [\ell og_2 D_{\theta,\ell}] + 1 \approx \sum_{\phi=\ell+2-2\cdot\theta}^{\ell+1} \log_2 \phi - \sum_{\phi=2}^{2\cdot\theta} \log_2 \phi .$$

Stage 2. The purpose of the second technological stage is to compare the estimates regarding the potential ability to eliminate various types of redundancy in the current cluster $Y(\theta)_u$. This refers to the use of coding methods which take into account its statistical and structural features.

For a θ-th structural cluster, the condition when the value $V_{\theta,\ell}$ exceeds the value $H(\theta)_u$ is checked. Here $H(\theta)_u$ is the lower limit of the amount of information contained on average in one $y'(\theta; d)_{i,j}^{(u)}$ element of the current θ cluster, taking into account its statistical features; $V_{\theta,\ell}$ is the upper limit of the amount of information that falls on one binary element $[y'(\theta; d)_{i,j}^{(u)}]_2$ of a cluster, taking into account structural features.

Therefore, the two values - $H(\theta)_u$ and $V_{\theta,\ell}$ - are compared. Two options are possible.

The first option, if the inequality holds:

$$H(\theta)_u \geq V_{\theta,\ell} . \quad (1)$$

The following values are used in this expression:

If inequality (1) holds, then:

1) the possibilities for reducing the amount of structural redundancy in a θ-th cluster exceed the possibilities for eliminating the amount of statistical redundancy;

2) most often for the lengths $v_{var}(\theta; g)_{i,j}^{(u)}$ and $v_{ufr}(\theta; g)_{i,j}^{(u)}$ of the codegrams $c_{var}(\theta; g)_{i,j}^{(u)}$ and $c_{ufr}(\theta; g)_{i,j}^{(u)}$ of syntactic description of the $y(\theta; g)_{i,j}^{(u)}$ components, the following inequality is fulfilled in the case of their statistical and structural coding:

$$v_{ufr}(\theta; g)_{i,j}^{(u)} = V_{\theta,\ell} < v_{var}(\theta; g)_{i,j}^{(u)}, \ g = \overline{1, G_\theta^{(u)}} , \quad (2)$$

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Here $v_{var}(\theta;\,g)^{(u)}_{i,j}$ is the length of NP codegrams $c_{var}(\theta;\,g)^{(u)}_{i,j}$ for clustered components $y(\theta;\,g)^{(u)}_{i,j}$; $v_{ufr}(\theta;\,g)^{(u)}_{i,j}$ is the length of the LU of the syntactic description of the code values $E(\theta;\,g)^{(u)}_{i,j}$ of the binary elements $[\,y(\theta;\,g)^{(u)}_{i,j}\,]_2$.

In this case, for the clustered components, a more effective syntactic description is built in the case of their coding in the structural-cluster space. For the specified option, the structural coding of the binary description $[\,y(\theta;\,g)^{(u)}_{i,j}\,]_2$ of clustered components $y(\theta;\,g)^{(u)}_{i,j}$ by the feature θ is carried out.

The second option. On the contrary, if between the values $H(\theta)_u$ and $V_{\theta,\ell}$ the following inequality holds:

$$H(\theta)_u \,<\, V_{\theta,\ell}\,, \qquad (3)$$

then two situations are possible, namely when:

a) the $v_{var}(\theta;\,g)^{(u)}_{i,j}$ length of the NP codegrams $c_{var}(\theta;\,g)^{(u)}_{i,j}$ for all $y(\theta;\,g)^{(u)}_{i,j}$ components in the cluster $Y(\theta)_u$ will be less than the $v_{ufr}(\theta;\,g)^{(u)}_{i,j}$ length of the LU codegram $c_{ufr}(\theta;\,g)^{(u)}_{i,j}$, i.e.:

$$v_{ufr}(\theta;\,g)^{(u)}_{i,j} = V_{\theta,\ell} > v_{var}(\theta;\,g)^{(u)}_{i,j}\,,\ g = \overline{1,\,G^{(u)}_{\theta}}\,, \qquad (4)$$

b) on the contrary, when between the values $v_{ufr}(\theta;\,g)^{(u)}_{i,j}$ and $v_{var}(\theta;\,g)^{(u)}_{i,j}$ the inequality (2) holds.

For the option when the condition (4) is fulfilled, the following can be asserted: due to the clusterization of transformants, the conditions are created for reducing a greater amount of statistical redundancy in comparison with the elimination of the amount of structural redundancy. In this case, element-by-element statistical coding is performed for the clustered components $[\,y(\theta;\,g)^{(u)}_{i,j}\,]_2$. Such coding can be organized based on the use of one of the modifications of a statistical code.

Otherwise, under the conditions of fulfillment of the inequalities (1) and (3), mixed results of the comparison of the lengths $v_{ufr}(\theta;\,g)^{(u)}_{i,j}$ and $v_{var}(\theta;\,g)^{(u)}_{i,j}$ of the codegrams of the clustered component $y(\theta;\,g)^{(u)}_{i,j}$ are possible. Under the specified conditions, the fulfillment of inequality (2) is caused by the fact that the entropy value $H(\theta)_u$ is the lower limit $v_{var}(\theta;\,g)^{(u)}_{i,j}$ of the lengths of NP codegrams. That is, $H(\theta)_u < v_{var}(\theta;\,g)^{(u)}_{i,j}$, $g = \overline{1,\,G^{(u)}_{\theta}}$. When the value $V_{\theta,\ell}$ is uniform within the current cluster $Y(\theta)_u$, then the relation is fulfilled: $v_{ufr}(\theta;\,g)^{(u)}_{i,j} = V_{\theta,\ell} = \text{const}$.

In this case, it is proposed to organize a preliminary selection of the $y(\theta;\,g)^{(u)}_{i,j}$ components to verify the fulfillment of one of the inequalities (2) or (4).

In the future, we will define such selection as structural selection in the space of statistical codes or structural-statistical (SS) selection of cluster components.

Accordingly, based on the results of such selection, one of the approaches to their coding will be introduced to the binary sequences $y'(\theta;\,d)^{(u)}_{i,j}$.

The structural selection of statistical codes can be technologically implemented by directly comparing the $v_{var}(\theta;\,d)^{(u)}_{i,j}$ lengths of the NP codegrams $c_{var}(\theta;\,d)^{(u)}_{i,j}$ with the $V_{\theta,\ell}$ length of the LU codegrams $c_{ufr}(\theta;\,d)^{(u)}_{i,j}$ of the current cluster.

Here, a typical selection of codegrams is done based on the following relation:

$$c(\theta;\,d)^{(u)}_{i,j} = c_{var}(\theta;\,d)^{(u)}_{i,j} \times$$
$$\times\,(1-\text{sign}(1-\text{sign}(v_{var}(\theta;\,d)^{(u)}_{i,j} - V_{\theta,\ell}))) +$$
$$+\,c_{ufr}(\theta;d)^{(u)}_{i,j}\cdot \text{sign}(1-\text{sign}(v_{var}(\theta;\,d)^{(u)}_{i,j} - V_{\theta,\ell}))\,.$$

The basis of this selection relation includes the sign functional *sign* with the help of which the identification of cases regarding the fulfillment of one of the inequalities (2) or (4) is achieved. The value $c(\theta;\,d)^{(u)}_{i,j}$ is a pointer to the class of the technological process.

Depending on the result of the comparison of the values $v_{var}(\theta;\,d)^{(u)}_{i,j}$ and $V_{\theta,\ell}$, the code representation of sequences $[\,y(\theta;\,d)^{(u)}_{i,j}\,]_2$, $d = \overline{1,\,D^{(u)}_{\theta}}$ is realised. Hence, greater adaptation of the structural selection to the features of statistical codes of the current cluster is achieved.

Such an approach requires the involvement of the information, namely the threshold $p'(\theta)^{(u)}_{i,j}$ of probabilities.

Then, if its value exceeds the probability, i.e.: $p'(\theta; d)^{(u)}_{i,j} > p'(\theta)^{(u)}_{i,j}$, then the corresponding NP codegram $c_{var}(\theta; d)^{(u)}_{i,j}$ will have a greater length $v_{var}(\theta; d)^{(u)}_{i,j}$ than the nominal $V_{\theta,\ell}$ length of the LU codegrams $c_{ufr}(\theta; d)^{(u)}_{i,j}$. The threshold $p'(\theta)^{(u)}_{i,j}$ value is chosen empirically based on the processing of the transformed segments for sufficiently informative video images.

Comparative evaluation of the effectiveness of different methods of encoding transformed video segments

The comparative evaluation of the created coding method is carried out according to the indicators of PSNR (Fig. 2) and the compression ratio k_{comp} (Fig. 3). The standardized approach is implemented in the JPEG platform.

The value of PSNR is estimated in the conditions of the probability of occurrence of bit errors at the level $P(\varepsilon) = 10^{-4}$. The error model corresponds to a discrete symmetric channel without memory.

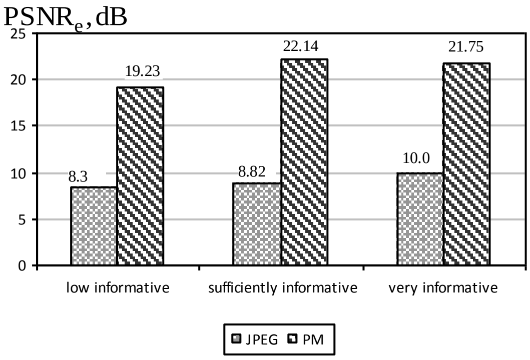

Fig. 2. Diagram of the dependence of the PSNR value on the degree of saturation of video images for various coding methods

According to the results of the analysis of the diagrams in Fig. 2, it can be concluded that the created method of transformant coding allows us to increase the level of fidelity of video images by the indicator of the peak signal/noise ratio from 30 to 70 % on average. The win amount depends on the level of informativeness of video segments. Accordingly, the conditions are created to ensure the value of PSNR at the level of 22-25 dB. Therefore, the conditions are created to ensure the requirements for the level of reliability of video images.

The dependence of the k_{comp} value on PSNR is realised for sufficiently informative video segments, which corresponds to the average level of saturation with small objects.

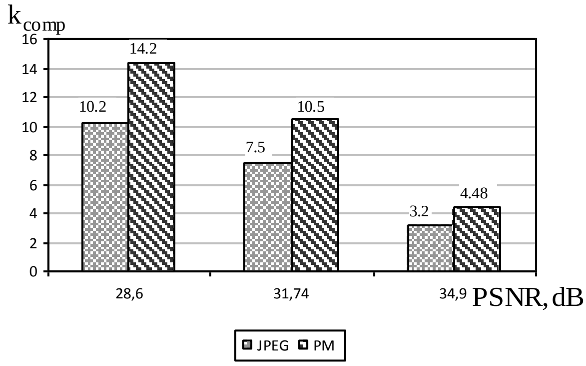

Fig. 3. Diagram of the dependence of the k_{comp} value on PSNR for different coding methods

Based on the analysis of the given diagrams, it can be stated that the created method for the given PSNR ensures an increase in the level of compression by an average of 13 %.

Conclusions

1. The potential effectiveness of representing the transformant in the clustered space by a number of series of units in the binary description of their components has been substantiated. The conditions are created for the clustered transformant to additionally reduce the amount of redundancy without a loss of information, including the amount of redundancy taking into account dependencies in the binary description.

2. A method of structural-statistical coding in the spectral-cluster space has been developed. This method is based on the principle of the duality of transformant components. It lies in the fact that a clustered component can simultaneously be considered as: an element of the statistical space of a cluster; an admissible element of a structural cluster.

The basic components of this technological approach are the following stages:

- the evaluation and comparison of estimates regarding the potential ability to eliminate various types of redundancy in a current cluster;
- the application of the coding methods that take into account its statistical and structural features;
- the structural-statistical selection of the components. This makes it possible to detect non-uniform prefix codegrams, the lengths of which exceed the nominal, locally uniform length of a cluster.

Scientific novelty. The method of structural-statistical coding of video segments in spectral space based on their clustering was created for the first time. The differences of the method lie in the fact that:

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1) a transformant component is simultaneously interpreted as an element of statistical and combinatorial cluster space;

2) ***the potential capabilities of eliminating various types of redundancy*** in the clustered transformant are taken into account.

Further research will deal with the development of methods for encoding marker arrays that contain information about transformant clusters.

Research results can be applied as follows:

1) as a component of complex technologies of video compression, namely at the stage of encoding transformed video segments;

2) for on-board complexes in the systems of video image formation and transmission;

3) for systems of video monitoring in terms of ensuring the conditions for increasing the resolution of video images;

4) on end nodes of infocommunication networks to reduce their bit load.

Contribution of the authors: the review and analysis of information sources – **Sergii Pchelnikov**; the analysis of technologies for restructuring the spectral space of a video segment – **Vitalii Kolesnyk**; the analysis of vulnerabilities of existing infocommunication technologies on onboard platforms – **Sergii Pchelnikov**; the justification of directions for the improvement of coding methods – **Andrii Krasnorutsky**; the justification of the approach to clusterization of video segments in the spectral space by a structural feature in the binary description of their components – **Vladimir Barannik**; the development of a model of statistical redundancy in the spectral-cluster space of a video segment – **Andrii Krasnorutsky**; creating an approach to coding in the spectral-cluster space – **Valeriy Barannik**, **Vitalii Kolesnyk**; the development of a clustered component selection model – **Vitalii Kolesnyk**, **Andrii Krasnorutsky**; the text of the previous version of the article – **Vladimir Barannik**; the analysis of the results of the comparison of different methods – **Pavlo Zeleny**; the selection and use of modeling tools and construction of diagrams – **Vitalii Kolesnyk**; editing and post-editing – **Andrii Krasnorutsky**, **Vitalii Kolesnyk**; formulation of conclusions – **Pavlo Zeleny**, **Andrii Krasnorutsky**, **Vitalii Kolesnyk**.

All the authors have read and agreed to the published version of the manuscript.

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МЕТОД СТИСНЕННЯ І ЗАБЕЗПЕЧЕННЯ ДОСТОВІРНОСТІ ВІДЕОЗОБРАЖЕНЬ В ІНФОКОМУНІКАЦІЙНИХ МЕРЕЖАХ

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Предметом досліджень в статті є методи стиснення відеозображень за умов забезпечення потрібного рівня достовірності в процесі доставки з використанням бездротових інфокомунікаційних мереж. **Метою** є розробка методів кодування відеозображень для збільшення рівня їх стиснення за умов забезпечення потрібної достовірності. **Завдання:** обгрунтувати підхід щодо структурної кластеризації трансформованих відеосегментів за умов збереження їх достовірності; розробити метод структурно-статистичного кодування трансформант в спектрально-кластерному просторі; провести порівняльне оцінювання ефективності різних методів кодування відеосегментів. **Методи** досліджень базуються на: математичних моделях оцінювання кількості статистичної та структурної надмірності в кластеризованому спектральному просторі відеосегментів, а також методах статистичного кодування. Отримані такі **результати.** Обгрунтовано потенційну ефективність представлення трансформанти в кластеризованому просторі за кількістю серій одиниць в двійковому описі їх компонент. Створено метод структурно-статистичного кодування в спектрально-кластерному просторі. Базовою складовою даного технологічного підходу є визначення оцінок щодо потенційної спроможності усунення різних видів надмірності в поточному кластері. Кількість надмірності скорочується з врахуванням статистичних та структурних особливостей кластеру. Порівняльне оцінювання виявило переваги створеного методу відносно методів кодування в стандартизованих платформах. Перевага досягнута за показником пікового відношення сигнал/шум, як найменш на 30 %, за коефіцієнтом стиснення в середньому на 12 %. **Висновки.** Наукова новизна отриманих результатів полягає в

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наступному: вперше створено метод структурно-статистичного кодування відеосегментів в спектральному просторі на основі їх кластерізації. Відмінності методу полягають у тому, що: компонента трансформанти одночасно інтерпретується як елемент статистичного та комбінаторного кластерного простору; враховуються потенційні спроможності усунення різних видів надмірності в кластерізованій трансформанті. Це забезпечує підвищення рівня стиснення відеозображень для заданого рівня їх достовірності.

Ключові слова: аерофотознімки; стиснення відеоданих; достовірність інформації; структурна кластеризація; кодування в спектрально-кластерному просторі; структурно-статистична надмірність.

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