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Image Compression and Protection Systems Based on Atomic Functions

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ABSTRACT Digital images are a particular type of data. They have numerous applications. Taking into account current challenges and trends, image compression and protection have to be ensured. Data format, which provides fast analysis of the image compressed, is needed. In order to satisfy a combination of these requirements, an appropriate information system should be developed. In this paper, we design such a system based on atomic functions (AF) that are solutions of special functional differential equations and, in terms of function theory, are as good constructive tools as trigonometric polynomials. AF-based image processing system (AFIPS), which satisfies the requirements considered, is developed. A core of this system is discrete atomic transform (DAT). Data protection feature of AFIPS is provided by the possibility to vary a structure of the procedure DAT. Constructive approximation properties of AF ensure high lossy and lossless image compression, as well as good image representation by DAT-coefficients. Software implementation of AFIPS is investigated. The results of test data processing are given.

KEYWORDS atomic function; image compression; image protection; discrete atomic transform.

I. INTRODUCTION

DIGITAL images are a particular type of data. They are widely used in remote sensing [1-3], medical imaging [4-6], computer vision [7-9], digital photography [10, 11], computer graphics [12, 13], etc. Also, there are many kinds of information systems that exploit them in order to provide various services. A lot of different image datasets have been collected [14-16]. Moreover, modern sensors are able to provide images of a very high resolution with a huge number of pixels. The total number of images, including digital photos, medical, aerial, satellite, and remote sensing ones, has increased explosively. This leads to great expenses required for storing, processing, and transferring them via networks. In order to solve this problem, data compression algorithms are used [17-19]. Many different methods have been developed, but none of them can be considered as a perfect tool, especially taking into account current challenges, in particular, the activity of cybercriminals.

Hackers' damage is huge. Unauthorized data access and its further inappropriate usage can lead to extremely negative consequences [20]. Therefore, high-level protection should be guaranteed, in particular, in the case of sensitive data, for instance, security cameras, landscape and medical images, as well as scans of documents. But not just these kinds of digital images must be protected. A serious threat is posed by the high level of development of machine learning methods combined with high computing capabilities provided by modern CPUs and GPUs. Indeed, using transfer learning [21, 22] and available open access models, which have been already trained, one may easily get highly efficient models that can be further used in the forbidden activity (deepfake is an example [23]). So, protected data storage and management is a requirement of great relevance.

In order to solve data protection problems, encryption algorithms are often applied [24, 25]. Also, visual encryption methods have been created [26], but their compressive properties are usually developed not well enough.

Note that, in most cases, compression algorithms do not provide protection, and encryption methods do not possess memory saving features. For this reason, a combination of several processing technologies is required, which increases needed computational resources. This has a number of negative implications. For instance, big data centers give a lot of thermal pollution [27]. Furthermore, a huge increase in computations may be unacceptable for low-resource and autonomous systems, for example, unmanned aerial vehicles [28], drones [29] and various gadgets [30].

Hence, design of algorithms, which ensure both compression and protection, is of particular relevance. Moreover, taking into account the need for fast processing and computer-based analysis of compressed images, for example, in IoT and edge computing systems [31, 32], an appropriate data format has to be provided.

For this purpose, one may improve some algorithms that already exist and are widely used. However, a number of different restrictions, which, in particular, are related to the mathematical tools applied or patents, may be a huge blocker. For example, discrete cosine transform (DCT) is a core of many image processing methods [34]. It possesses a combination of convenient features, including good approximation and energy compaction properties [35]. Nevertheless, since trigonometric functions are not compactly supported, the complexity of DCT is non-linear, which is of particular importance when processing big data. Also, it is non-compactness and some other functional properties that prompted the creation of new classes of constructive tools such as splines [36], atomic functions [37, 38] and wavelets [39]. So, a development of new algorithms, which are based on non-classic mathematical functions, can be expedient.

In this paper, atomic functions (AF) system is considered. These tools were introduced in the early 70ths of the 20th century [37, 38]. In general, that time can be characterized by a rapid growth in the number of problems for which classical mathematical tools were not enough due to limited computing capabilities. New functions were proposed, including wavelets that are widely applied, in particular, in image compression [17, 40].

Atomic functions are closely related to wavelets. Indeed, by the definition [38], a function is called atomic if it is a solution with compact support of linear functional differential equation with constant coefficients and linear argument transformations. When constructing some special wavelet systems, solutions of functional equations, which are partial cases of the differential equations mentioned above, are frequently used. Therefore, the application of atomic functions to image processing makes sense. Moreover, atomic functions combine a set of advantages, including good approximation properties, compactness and smoothness, that provide fast data expansion algorithms [41]. Nevertheless, information technology construction using these tools requires a systematic approach, which ensures sustainable functioning.

The aim of the current paper is to develop principles of construction of AF-based information systems, which provide image compression and protection in combination with a such data format that ensures low resource intensive processing and analysis of the compressed data. The methodology for constructing such systems proposed in the further sections forms a novelty of the current research, and a contribution is a development approach that is applied to ready-to-use software.

II. FORMULATION OF THE PROBLEM

Application of atomic functions to image processing, which provides a combination of compression and protection features with further analysis-oriented data format, requires an appropriate and particular approach. There are the following reasons for this. AFs are real-valued functions of a real argument. There are several ways to apply them. The first one is the use of a special basis of spaces of AF linear combinations. It can be, for instance, a system of the function *Fup(x)* shifts [37, 38], as well as non-stationary wavelets [41]. Another way is an application of the so-called generalized Taylor series [38]. In spite of the fact that these approaches are totally different in terms of function theory, their common feature is the following: both applying some special basis and some Taylor-like series requires an input, which is a real valued function. In other words, AF-based constructive tools mostly provide processing and analysis of functions of continuous argument.

In theory, a digital image is considered as a two-dimensional function $f(x,y)$ [34]. For this reason, a direct application of multidimensional AF-based tools to such an input seems to be natural and, in some sense, trivial. But in practice, an image is given by a matrix and, hence, $f(x,y)$ is a function of discrete argument, i.e. $x \in X$ and $y \in Y$, where X and Y are discrete sets. Therefore, one cannot use methods of AF theory directly.

In order to process images by some system of functions, discrete data transforms are used [34, 35]. In particular, trigonometric functions are applied in the form of DCT. Another important example is discrete wavelet transform (DWT) [35, 40].

When applying AF to image processing, it is proposed to use discrete atomic transform (DAT) [41]. It is DWT based on non-stationary infinitely smooth wavelets with a compact support. One-dimensional DAT takes an array of real or integer elements and computes an array of DAT-coefficients, which are, in general, floating-point values.

Multidimensional DAT is constructed using one-dimensional DAT. In particular, matrix transform provides a processing tool that can be used in image processing.

As it has been discussed in [42, 43], there is a huge number of various structures of two-dimensional DATs that can be used in order to ensure data protection features.

Since an output of DAT is a set of floating-point values, it requires an additional processing step if compression is desired.

The reason is the following: in many cases, input is given by a set of integers of a limited range (in the case of RGB-images, this range is $\{0, 1, \ldots, 255\}$ for each color component); a number of bytes, which are required for storing each of them, is less than bytes size needed for each DAT-coefficient.

The classic solution to this problem is an application of the following scheme:

$$data \to discrete\ transform \to quantization \to \\ \to encoding \to compressed\ data. \quad (1)$$

This approach is employed in many methods, in particular, image compression. For instance, the algorithms JPEG, JPEG2000, WebP, AGU, ADCTC and many others are based on it [18, 19]. Also, in discrete atomic transform (DAC) [42, 43], which is an image compression algorithm constructed using the procedure DAT, the classic scheme presented above is implemented.

When applying quantization, one has:

$$\omega = Round\left(\frac{w}{q}\right), \quad (2)$$

where w is an initial value, q is a coefficient of quantization and ω is quantized value. This implies that each algorithm, which uses this step, is lossy. In other words, decompressed and source data are, in general, different. Presence of distortions, in some cases, is forbidden. For example, in text and medical image compression, information loss is often not allowed.

Nevertheless, some loss of quality may be acceptable in other image compression applications, especially if compression is visually lossless. Wherein, a mechanism, which provides the desired distortions in terms of some given metric, is a requirement. There are many indicators for measuring loss of quality, for example, maximum absolute deviation (MAD), root mean square error (RMSE) and peak signal-to-noise ratio (PSNR):

$$MAD = max_{k=1,\ldots,N}|x_k - y_k|,$$
$$RMSE = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(x_k - y_k)^2},$$
$$PSNR = 20log_{10}\left(\frac{MAX}{RMSE}\right),$$

where $X = (x_1, \ldots, x_N)$ and $Y = (y_1, \ldots, y_N)$ are the source and the reconstructed data, respectively. The relevance of each of them is specified by practical purposes. An existence of quality control mechanism means the following: there is a set of steps, which define such settings of the algorithm that provide the desired quality of result in terms of the required metric.

We note that settings of lossy image compression algorithms, based on the classic scheme shown above, can be divided into two main classes: parameters and hyperparameters.

Parameters specify quantization coefficients and encoding settings. At the same time, hyperparameters define discrete data transform. For example, in DCT-based image compression algorithms, the size of the DCT block should be considered a hyperparameter. In DAT-based image processing, hyperparameters are the atomic function applied and a structure of DAT. Their variation leads to principal changes of the algorithm and its features. In particular, coefficient quantization choice approach and encoding settings must be modified.

Further, in many cases, for example, when processing medical images or evidence data, lossless compression is a requirement. For this purpose, in [43], it was proposed to complement files, which are obtained using lossy compression, with the difference between source and reconstructed data.

Thus, when developing applied information image processing technologies based on atomic functions, it is necessary to take into account a set of various closely interconnected features. This requires creating an appropriate information system. Such a system must provide a combination of the following features:

1) data compression;
2) data protection;
3) low complexity processing;
4) data representation, oriented on further direct analysis;
5) ability to control parameters and hyperparameters.

The task of the current research is to develop an AF-based information system that satisfies the requirements mentioned above. For this purpose, we use methods of atomic functions theory, image processing, information theory and algorithms complexity analysis. Unlike previous works on AF- and DAT-based image processing, here we focus on an integrated approach, rather than on individual aspects.

To solve the stated problem, we propose to extend the scheme (1). We design a system that takes input data, which is a digital image, and outputs a byte array. Applying the AF-based discrete transform ensures that storing this array requires less memory than the source image. Data protection feature is provided by the possibility to vary the structure of the DAT procedure. Further, each processing step is described in more detail; the structure of the system settings and their use is specified as well.

III. ATOMIC FUNCTIONS BASED IMAGE COMPRESSION AND PROTECTION SYSTEM

In this Section, AF-based image processing system (AFIPS), which satisfies the requirements considered, is developed. First, its structure is presented. Next, the principal properties are investigated. Then, implementation features are discussed, and the results of test data processing follow.

A. STRUCTURE

In Fig. 1, AF-based image processing system (AFIPS), which is supposed to combine data protection and compression features, is proposed. Consider it in more detail.

An input is a matrix of N-channel digital image. If it is a grayscale 8 bit image, then $N = 1$. In the case of 24 bit full color image processing, $N = 3$ and it is given by a matrix, each element of which consists of three components: red (R), green (G) and blue (B).

An output is a byte array that, further, can be stored in a binary file, as well as transferred via networks.

Image processing provided by AFIPS is defined by a group of settings that consists of preprocessing mode, protection key and quality loss mode specifications. Note that they also can be considered as special type inputs.

Preprocessing mode determines actions that must be applied to the input image matrix. In image processing [34], the following procedures are the most common:

– color space transform; a particular case is RGB-to-YCrCb transform that provides computation of three matrices of luma (Y) and chroma (Cr, Cb) components;

– chroma-subsampling, which may follow RGB-to-YCrCb transform, when processing 24 bit full color images;

– block-splitting, which means that a source matrix is split into blocks of the fixed size (in this case, their height and width should be defined).

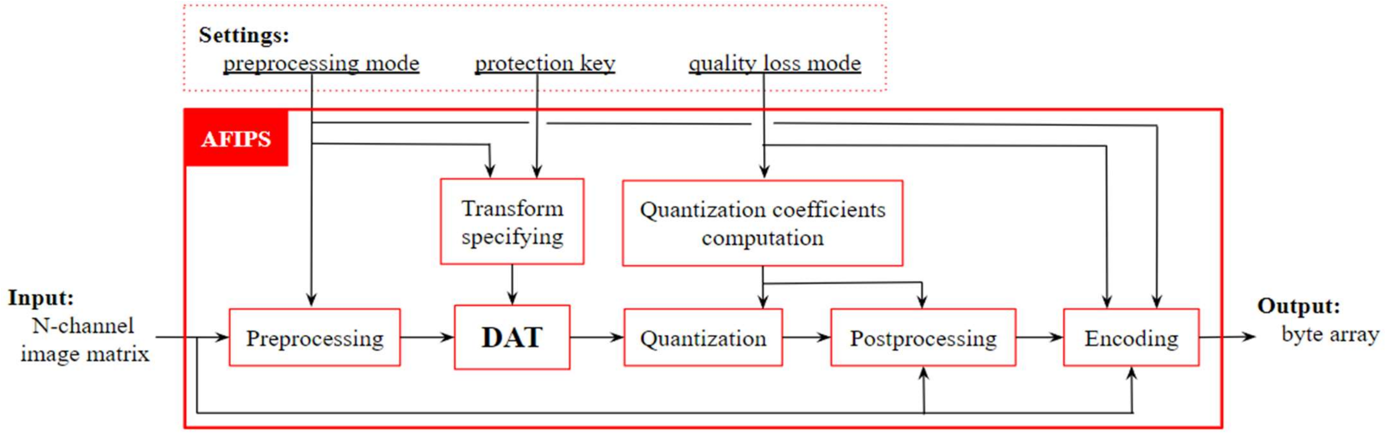

Figure 1. Atomic function-based image processing system (AFIPS) providing compression and protection features.

Note that the latter transform can be applied to both full color and grayscale images, as well as to multi-channel ones.

These procedures can be combined. For instance, in the algorithm JPEG, when compressing full color images, the transform RGB-to-YCrCb, chroma subsampling and splitting into 8 by 8 blocks are applied.

Also, preprocessing can be skipped. Otherwise, parameters of this stage are also encoded, in order to provide correct reconstruction. Besides, in general, they specify a structure of the procedure DAT that is applied at the next stage.

Another element of settings is a protection key, which is given as a bit set. We propose to use it in order to specify a structure of DAT. In order to provide a protection feature, it is suggested to store this key separately from the rest of the output data.

Finally, quality loss mode determines what compression is used: lossless or lossy. In the case of lossy image compression, a parameter, which specifies a level of distortions, is supposed to be provided. This data defines coefficients of quantization. Our suggestion is to store it with output, which ensures further correct reconstruction of the image processed.

Next, then the main computations are performed in the following order:

1) **preprocessing**: an N-channel input image matrix A is preprocessed; an output of this step is the set $\{B_1, \dots, B_M\}$ of matrices, the computation and quantity of which are specified by preprocessing mode;

2) **DAT**: the DAT procedure is applied independently to each matrix B_k of the previous step output; a structure of DAT is defined by the transform specification, which is determined by protection key and preprocessing mode; an output is the set $\{W_1, \dots, W_M\}$ of matrices of DAT-coefficients;

3) **quantization**: using the formula (2), elements of each matrix W_k are quantized; wherein, coefficients of quantization are defined by quality loss mode; the set $\{\Omega_1, \dots, \Omega_M\}$ of matrices of quantized DAT-coefficients constitutes an output of this step;

4) **postprocessing**: if lossless compression is not required, then postprocessing step is skipped; otherwise, it is suggested to obtain data that provide a precise reconstruction of the image processed; for this purpose, it is suggested to perform the following steps:

4.1) dequantize matrices $\{\Omega_1, \dots, \Omega_M\}$ using the formula, which is inverse to (2);

4.2) apply inverse DAT to each matrix computed at the previous step;

4.3) by applying inverse preprocessing, compute N-channel matrix R that is a reconstruction of the source matrix A;

4.4) compute the difference matrix $D = A - R$; output is the set $\{\Omega_1, \dots, \Omega_M\}$, as well as the matrix D if lossless compression is required;

5) **encoding**: the following order of data encoding is proposed:

– number of channels and sizes of the matrix A;

– preprocessing and quality loss modes;

– blocks of the matrices $\{\Omega_1, \dots, \Omega_M\}$, which constitute the main part;

– the difference matrix D, when applying lossless compression mode.

A byte array, which consists of the header and main parts, is an output of AFIPS. The header contains information about image characteristics (height, width and number of channels), as well as specifications of preprocessing and loss of quality modes. When implementing the proposed approach, one should also specify bit size of each value. Additionally, this part can be encrypted or even stored separately from the rest of data, which improves protection.

In Fig. 2, data workflow in AFIPS is shown.

The main part of AFIPS output contains quantized DAT-coefficients that are compressed using entropy encoding [17]. Various approaches, including Huffman codes (HC) and context adaptive binary arithmetic coding (CABAC), can be applied for this purpose. When implementing the image processing system suggested, the encoder choice should be based on the priority of requirements. It is well-known that, in general, CABAC provides higher compression than HC in combination with much higher complexity [17]. So, it is not recommended to use this method if computational capabilities are extremely poor.

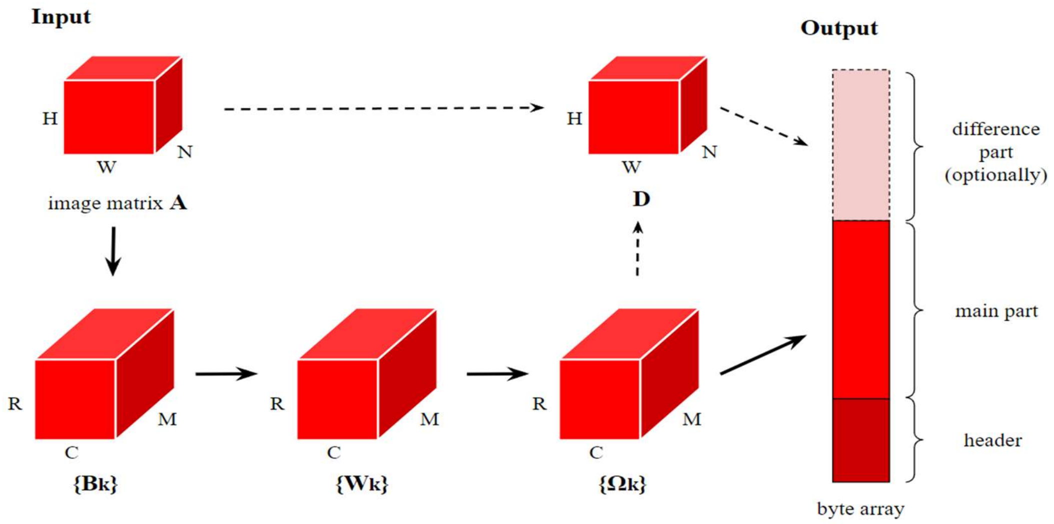

Figure 2. Data workflow in the information system AFIPS.

In this case, HC or some other low resource intensive data compression algorithms, for instance, recursive group coding [44], can be applied.

Besides, like any other DWTs, the DAT procedure provides block structured matrices of wavelet-coefficients. We propose to encode these blocks separately.

Finally, AFIPS output optionally ends with compressed differences' matrix. In order to choose an appropriate encoding method, it is proposed to use the same approach, which is presented above.

So, a structure of AFIPS has been described. Now, we consider its properties.

B. PROPERTIES

The proposed information system AFIPS is expected to provide a combination of data compression and protection features with low complexity processing, as well as parameters/hyperparameters control mechanism and image representation oriented on further analysis. It is a set of fundamental properties of the atomic functions applied that ensures the efficiency of this system.

Consider the following atomic functions:

$$up_s(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{itx} \prod_{k=1}^{\infty} \frac{sin^2(s(2s)^{-k})}{s^2 t(2s)^{-k} sin(t(2s)^{-k})} dt,$$

where $s = 1, 2, 3, \ldots$. In spite of the complicated representation by Fourier integral, their values can be easily computed using fast dynamic algorithm that was suggested in [45]. Moreover, as it is shown, values of $up_s(x)$ are rational at the points of dense grids and can be found exactly. Furthermore, spaces of linear combinations of up_s-translates have good approximation properties and locally supported wavelet basis [41]. Besides, they are infinitely differentiable, and, hence, are convenient constructive tools for smooth functions.

The DAT procedure is constructed using up_s-based non-stationary infinitely smooth locally supported wavelets [41]. It also follows that this wavelet system combines a simplicity of computation with good approximative properties.

Locality of wavelets, which constitutes a core of DAT, provides fast data expansion. Indeed, its time complexity is linear in the size of the data processed [41]. In other words, when processing $R \times C$ matrix B, a time of computation of the matrix W of the corresponding DAT-coefficients is of the order $O(RC)$. Moreover, matrix W has a block structure. There are blocks of low-frequency and high-frequency wavelet coefficients. Since the applied wavelets constitute a basis of functional spaces, which are asymptotically extremal for approximation of smooth functions [37, 38, 41], low-frequency and high-frequency DAT-coefficients contain respectively significant and insignificant image data. It is this feature that provides image compression by AFIPS. Indeed, after quantization, high-frequency DAT-coefficients have a small range and, hence, can be well-compressed [17]. Besides, simplicity and accuracy of the calculation of up_s-function values ensure insignificant computational errors, when applying DAT. Also, smoothness of $up_s(x)$ provides high compression ratio (CR):

$$CR = \frac{size\ of\ source\ image}{size\ of\ compressed\ image},$$

especially, when processing digital photos as well as images that have been previously compressed by other methods, in particular, DCT-based ones.

Next, data protection property of AFIPS is ensured by the existence of more than 10^{110} of DAT structures [42, 43]. Indeed, in order to reconstruct the image compressed, an appropriate procedure, which is inverse to direct DAT, has to be applied. In combination with a great number of different DAT structures, this feature provides high level data protection if structure specification is not stored with the main data. In this case, processed image content remains inaccessible even if some unauthorized persons get access to them.

Further, by construction, AFIPS has built-in image processing parameters/hyperparameters control mechanism. The principal blocks are "Transform specifying" and "Quantization coefficients computation" (see Fig. 1). It is supposed that the first one is an injective function, which maps its inputs (preprocessing mode and protection key) onto a set of all DAT structures considered. We stress that data protection requirements specify an implementation of this block. The second block is also a function. Like in many existing methods, for example JPEG, it is proposed to construct this mapping in the form of a function of a single variable Q that varies from *1* to *100*. The case $Q = 100$ corresponds to the lossless compression mode. If $Q < 100$, then lossy compression is obtained. In order to provide the desired value of the metrics *MAD*, *RMSE* and *PSNR*, it is suggested to use the quality loss control mechanism that was described in [42]. In this approach, coefficients of quantization are specified by the special parameter denoted by *UBMAD*. In order to apply *UBMAD*-based computation of quantization coefficients to AFIPS, we propose to use the function *UDMAD = UBMAD(Q)* that is a bijective mapping of the interval [1, 100) onto a set of *UBMAD* values. In addition, when *Q = 100*, i.e. lossless mode is desired, this function returns such *UBMAD* that ensures the maximum value of *CR*.

In addition, since the main part of the byte array, which is an output of AFIPS, contains blocks of compressed DAT-coefficients, further analysis oriented data representation feature is guaranteed. Indeed, these blocks correspond to orthogonal AF-based wavelet layers that constitute a basis of spaces with good approximation properties [37, 38, 41], and it is further processing and analyzing of DAT-coefficients that provides the feature mentioned above. Besides, this implies that a complete reconstruction of the compressed image is not required, which saves computational resources.

Finally, the proposed approach provides fast data transfer from lossless to lossy form. Indeed, in order to perform it, one should remove the difference part (see Fig. 2). Actually, when lossless mode is applied, an output byte array can be considered in a sense as a raw image format that is a feature of particular importance, especially for professional digital photography.

C. IMPLEMENTATION AND EXPERIMENTAL RESULTS

The structure of AFIPS and its properties are given above. Below, an implementation of these theoretical investigations and the results of experiments are presented. Currently, we use the software "ATools Software Development Kit: image processing technologies using finite functions" [46] created by a group of independent developers. This computer program is an illustration of implementing AFIPS design principles. Here, the function $up_{32}(x)$ is used and 24 bit full color image processing is supported. An input is RGB matrix that can be loaded directly from a BMP-file or obtained from an image file of another format, in particular JPEG, PNG, WebP, etc. An output is a file of a special format. Its header part contains a group of bytes specifying image size, quality loss and preprocessing modes. Loss of quality mode is one- byte integer from the range *[1, 100]*. Preprocessing mode is also described by one-byte integer. Block splitting and chroma subsampling modes are supported. In the software considered, quantization coefficients are computed using formulas given in [42]. Quantized DAT-coefficients are compressed by CABAC with two data models that use information about the previous bit encoded. The same approach is applied for compressing the difference matrix *D*. Also, a trivial protection key system is implemented. Currently, a protection key is defined by four digits pin code and is not stored in the protected file.

Now, we investigate the efficiency of the considered implementation of AFIPS. In this research, the set of 93 satellite images of the European Space Agency (https://www.esa.int) is used. A small copy of a typical image and its true size fragment are given in Fig. 3 and Fig. 4. As it can be seen, the test sample shown contains a lot of small objects and sharp changes of color intensity, as well as domains of relatively smooth intensity variations.

Preprocessing and quality loss modes are varied, and each test image is processed. After that, decompression is applied, and values of MAD, RMSE, PSNR, and CR are computed. Wherein, the same pin code is used. Averaged results are presented in Tables 1 - 3. Also, Table 4 shows the required memory expenses.

From Tables 1 and 2, it follows that the regular and block splitting modes provide nearly the same mean values of performance indicators. Nevertheless, Table 4 shows that the first one ensures greater overall memory savings although the difference is insignificant.

Table 1. Test data compression results: correct pin code, regular mode

Quality mode Q	Performance indicators			
	MAD	RMSE	PSNR, dB	CR
70	38.6	4.47	35.24	8.31
80	24.76	3.15	38.25	5.49
90	17.19	2.28	41.00	4.17
99	9.34	1.27	46.04	2.46
100	0	0	-	1.56

Table 2. Test data compression results: correct pin code, block splitting mode

Quality mode Q	Performance indicators			
	MAD	RMSE	PSNR, dB	CR
70	45.20	4.50	35.20	8.32
80	28.95	3.16	38.21	5.46
90	20.18	2.30	40.96	4.15
99	11.33	1.28	45.99	2.43
100	0	0	-	1.55

Table 3. Test data compression results: correct pin code, chroma subsampling mode

Quality mode Q	Performance indicators			
	MAD	RMSE	PSNR, dB	CR
70	114.57	5.85	33.08	11.50
80	112.53	4.91	34.70	8.22
90	111.14	4.39	35.78	6.53
99	110.59	3.93	36.91	4.16
100	0	0	-	1.60

Figure 3. Small copy of the image "Guinea-Bissau and the Bissagos islands".

Figure 4. True size fragment of the image shown in Fig. 3.

Table 4. Total memory expenses, MB

Quality mode Q	Preprocessing mode		
	regular	block splitting	chroma subsampling
70	981.08	986.99	682.48
80	1434.05	1447.78	931.15
90	1855.24	1875.90	1158.35
99	3057.14	3094.95	1784.43
100	4744.43	4755.61	4621.26
ZIP	6080.33		
PNG	6673.36		
BMP, source	7395.75		

Further, it follows from Table 3 that chroma subsampling guarantees better compression than two other modes for each Q. However, it produces considerably greater distortions measured by *MAD*, *RMSE* and *PSNR*.

We note that aggregated test data processing results are not presented due to paper page limitations. One may find the source and reconstructed images as well as the values of quality loss metrics at the following link to the Google drive folder: https://drive.google.com/drive/folders/1yQhdV4mm9 I4kqaR81xYe8qWCOWIGN3HL?usp=share_link.

In addition, we have applied a decompression with the wrong pin code. The regular preprocessing mode and quality loss mode $Q = 70$ are used. The typical reconstruction result is shown in Fig. 5. Other reconstruction results are nearly the same. One may check them at the link https://drive.google.com/drive/folders/1zMgm-16tTXVInglq GyRTapWVsv8WHpRT?usp=share_link. Moreover, the evaluation of quality loss metrics provides the following:

$$min(MAD) = 255, \quad (3)$$

$$min(RMSE) = 93.63, \quad (4)$$

$$max(PSNR) = 8.70 \text{ dB}. \quad (5)$$

Next, by comparing the test image shown in Fig. 3 with Fig. 5, which is its version reconstructed using an incorrect pin code, one may see that these pictures are visually different. In combination with (3) - (5), this illustrates the data protection feature of the approach applied.

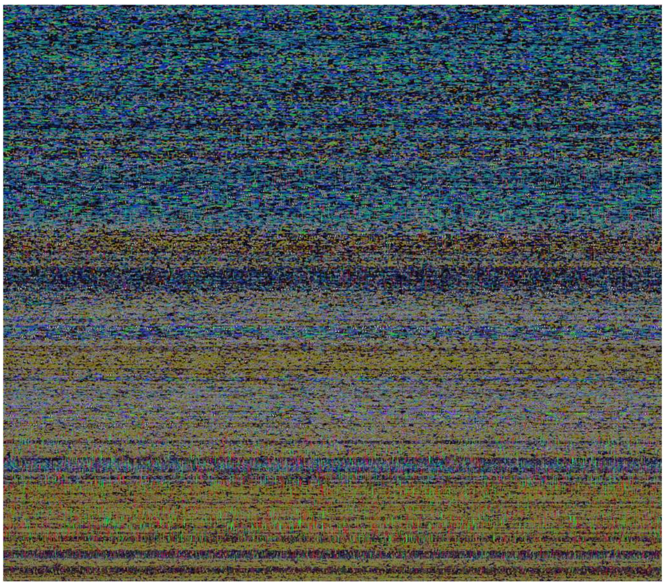

Figure 5. Reconstruction of the image shown in Fig. 3 with incorrect pin code (wrong protection key).

IV. DISCUSSION

In the previous Section, the system AFIPS is designed. The proposed approach takes into account the principal features of atomic functions, which constitute a core of the DAT procedure. Test data processing results prove that the proposed structure, which is theoretical, can be implemented in the form of software. Moreover, it is shown that all requirements are satisfied. Besides, this implies that AFIPS usage provides better lossless compression than ZIP and PNG, which are widely applied. Also, the equalities (3) - (5) illustrate that data protection feature is achieved. Furthermore, the following is recommended:

1) one should apply block splitting mode, since it provides the same compression results in terms of MAD, RMSE, PSNR and CR in combination with lower spatial complexity; although, it may occur that regular preprocessing requires lower time expenses, when using parallelization of computations;

2) chroma subsampling should not be used, when processing digital images of complex content; however, if lossless compression is a requirement, then it is this preprocessing mode that should be applied; moreover, this mode provides faster results, since smaller matrices of chroma components are processed.

We note also that, since blocks of DAT-coefficients, which correspond to different frequency bands, are stored in compressed image file separately, further image analysis and applying machine learning can be carried out directly to these data without the necessity of full image decompression.

Finally, in the current AFIPS implementation, a simple version of CABAC is used. For this reason, higher compression ratio can be guaranteed, for instance, by applying a greater number of data models.

V. CONCLUSIONS

In this paper, the atomic function based image processing system, which provides a combination of compression and protection features, has been designed. Moreover, as it has been discussed, the image processed is stored in the format that ensures its fast analysis and direct application of artificial intelligence methods. Also, its software implementation has been considered and analyzed in terms of image compression performance indicators. By processing a set of complex content test images, it has been shown that significant memory saving is obtained, and data protection feature is ensured. Notice that, in [47], discrete atomic transform and discrete cosine transform have been compared in terms of current trends, and it has been proved that the first data transform should be preferred.

The proposed structure of the information system can be extended. In particular, the DAT procedure can be replaced by another one. For instance, progressive DCT-based image compressor is investigated in [47], and its software implementation may be considered as an application of the principles suggested in the current paper.

Hence, further development of the proposed AFIPS principles and their applications are promising. For instance, its architecture can be applied in Internet of Things systems providing current information transferring requirements [48, 49]. Besides, applying DAT-based image representation can be used as a core of machine learning algorithms for edge computing [50]. In addition, its data protection feature is relevant, especially taking into account privacy protection requirements [51, 52] and contemporary image encryption approaches [53, 54].

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