Evaluation of the Effectiveness of Applying the Image Quality Metrics for Acquisition the Steganograms

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In paper is considered to the analysis of type and evaluation of the level of image distortion by data embedding into frequency domain. The four groups of image quality metrics (spatial and spectral distortion metrics, correlation characteristics and visual quality metrics) are analyzed on the 100 digital images with 8 Megapixels resolution by variation of embedding level from 10% to 90%. Such approach gives us a possibility to make conclusion that applying of specified correlation characteristics (Czenakowski Distance, Mean Angular Difference) and visual quality metrics (Normalized Histogram Similarity) allows reveal the fact of data embedding in frequency domain of images with high precision.

Introduction

The growth of amount the multimedia files, which are processing, stored and transmitting by telecommunications, allows using such files as containers for data embedding. One of the most often used containers for data embedding is digital images (DI). Considerable quantity of methods and transforms, which are used for processing such files (visual quality enhancement, compression, noise cancellation etc.), gives opportunities for creation the multistage data embedding methods for increasing the robustness of steganogram to possible passive and active attacks (disclosure and destruction, correspondingly).

Modern tendency of data hiding in DI is using different transformation (e.g. Discrete Cosine Transform (DCT), Discrete Wavelet transform (DWT), Discrete Fourier Transform (DFT) etc.) as "basis" for steganographic methods. Usage of features the DI representation in transformation domain allows reducing the container distortion by data hiding and, consequently, decreases the effectiveness of passive attacks on steganograms. Due to this is represented the interests of analysis the type and level of DI distortion by steganogram forming for elaboration the recommendations for developing more precise methods of passive steganalysis.

Related work

Despite of significant quantity of publicly available steganographic methods, which are based on data embedding in DI, there are limited amount of works, which are devoted to researching the fine structure of container distortion by data embedding.

On the work [1] was proposed to use of various perceptual and differential metrics for assessment the "quality" of embedding method and were produced the corresponding analysis of the most widespread Least Significant Bits, spread spectrum and frequency domain based methods. The results of analysis of the DI distortion by JPEG compression, as one of basic attacks of steganographic system, are represented in the work [2]. The significant limitation of practical usage the mentioned works is analysis only separate groups of image quality metrics (spatial distortion metrics and correlation characteristics) and absence the statistical data for image quality metrics (IQM) values by data hiding in transformation domain.

The goal and contribution

The work is devoted to determination the most effective IQMs which can be used for revealing the distortion of fine structure the DI by data embedding in frequency domain (FD) the images by different methods. The choice of such methods the data embedding is caused by significant amount of transformations, which are used for analyzing the images in frequency domain and, respectively, can be applied for secret message hiding.

For comprehensive and versatile analysis the DI distortion by data embedding in FD are examined the 11 image quality metrics, which are divided into 4 groups – spatial distortion metrics, spectral distortion metrics, correlation characteristics and visual quality metrics. To the best of our knowledge, there is firstly produced the detailed and versatile analysis the container distortion by secret message embedding into FD.

The remainder of the paper is organized as followed. In the next section the short description of examined steganography methods are represented. Then we consider the groups of image quality metrics, which are used for analysis the image distortion (ID). The results of assessment the ID by using different steganographic methods are represented in 3^{rd} section.

Embedding data into frequency domain of digital images

The choice of type the DI transformation for data hiding often is produced for prevail the 2 goal: reduce the visual distortion of images after secret message embedding and increase the robustness of formed steganogram to possible active attacks (compression, noise cancellation, filtering etc.). Mentioned aims are contradictory – increasing visual quality of DI is achieved by reducing the energy of noise (i.e. embedded data), which is led to decreasing the robustness of secret message to active attacks, and vice-versa. Usage the features of specific type of image transformation gives opportunity to achieve the certain “balance” between covertness and robustness of steganogram.

Significant amount of modern graphical formats is based on using the DCT and DWT for effective compression the DI [3]. Due to this usage of such transformation for data hiding in images, allows to increasing the robustness of embedding – secret message is integrated in DI with a glance of peculiarities the corresponding graphical format. The usage of DFT for image processing is limited because of necessity working with complex numbers, which is computational cost-based process, and worse opportunities of image compression in comparison with DCT and DWT.

For analysis the embedding methods is used the test packet of 100 DI. The parameters of used container and steganodata are represented at Table 1.

Table 1. Parameters of used containers and steganodata

Parameter	Container	Steganodata
Size (pixels)	3264×2448	567×463
Color depth ($\frac{\text{bits}}{\text{pixel} \times \text{color plane}}$)	8	8
Resolution ($\frac{\text{dots}}{\text{inch}}$)	72	72
Graphical format	JPEG TrueColor (v1.1)	BMP (True Color)

In the work are analyzed the usage of following types of image transformation for data embedding in FD:

- Discrete Fourier Transform [4];
- Discrete Cosine Transform [5];
- Discrete Wavelet Transform [6], [7] (designated as DWT/1 – [6] and DWT/2 – [7]).

The metrics for evaluation the distortion of digital images

There are considered the usage of 11 image quality metrics for analyzing the type and estimation the level of DI distortion after data embedding. The IQM are divided into 4 groups according to the type of ID, which is revealed by usage the specified metrics:

1. Spatial distortion indices:
   - Maximum Difference (MD) – is used for estimation the maximum pixelwise differrence between the initial and obtained DI;
   - Mean-Squared Error (MSE) – is integral measure of digital images discrepancy;
   - Image Fidelity (IF) – this indice is measure of energy difference between digital images;
2. Spectral distortion indices:
   - Normalized Spectral Magnitude Distortion (NSMD) – is used for measure of changes the share of separate spatial frequencies in obtained DI;
   - Normalized Spectral Phase Distortion (NSPD) – is used for assessment the accuracy of DI reconstruction in spatial domain by inverse DFT;
3. Correlation characteristics:
   - Normalized Cross-Correlation (NCC) – is degree of similarity between initial and obtained digital images;
   - Czenakowski Distance (CD) – is pixelwise measure of similarity between the digital images;
   - Mean Angular Difference (MAD) – this indice is used for assessment the pixelwise color distortion by image processing;
4. Visual quality metrics:

- Peak Signal-to-Noise Ratio (PSNR) – metric, which is wide used for estimation the visual quality by digital images processing;
- Normalized Histogram Similarity (NHS) – is used for measure the changes of pixel's luminance distribution and, correlondingly, the image contrast;
- Structure Similarity (SSIM) – composite index for estimation the correlation degree, measure of discrepancy between brightness and contrast of initial and obtained DI.

It should be mentioned that instead of utilized Histogram Similarity, Spectral Magnitude Distortion and Spectral Phase Distortion metrics are used theirs normalized variant for shown the average distortion per each pixel.

Formulae for computation the IQM by comparison the images C and S with size $M \times N$ (pixels) are represented below [8] [9]:

1. Spatial distortion indices:

$$MD = \max_{x,y} |C_{x,y} - S_{x,y}|;$$

$$MSE = \frac{1}{MN} \sum\nolimits_{x,y} (C_{x,y} - S_{x,y})^2;$$

$$IF = 1 - \frac{\sum_{x,y} (C_{x,y} - S_{x,y})^2}{\sum_{x,y} (C_{x,y})^2};$$

2. Spectral distortion indices:

$$NSMD = \frac{1}{MN} \sum\nolimits_{u=0}^{M-1} \sum\nolimits_{v=0}^{N-1} |A_C(u,v) - A_S(u,v)|^2,$$

$$NSPD = \frac{1}{MN} \sum\nolimits_{u=0}^{M-1} \sum\nolimits_{v=0}^{N-1} |\phi_C(u,v) - \phi_S(u,v)|^2,$$

where $A(u,v)$, $\phi(u,v)$ – correspondingly, amplitude and phase spectrums of 2D-DFT;

3. Correlation characteristics:

$$NCC = \frac{\sum_{x,y} (C_{x,y} \cdot S_{x,y})}{\sum_{x,y} (C_{x,y}^2)};$$

$$CD = \frac{1}{MN} \sum\nolimits_{x,y} \left[1 - 2 \frac{\sum_{k=1}^{3} \min\{C_k(x,y), S_k(x,y)\}}{\sum_{k=1}^{3} \{C_k(x,y) + S_k(x,y)\}} \right];$$

$$MAD = 1 - \frac{1}{MN} \sum\nolimits_{x,y} \left[\frac{2}{\pi} \arccos \left\{ \frac{\langle C_{xy}; S_{xy} \rangle}{\|C_{xy}\| \cdot \|S_{xy}\|} \right\} \right],$$

$$\langle C_{xy}; S_{xy} \rangle = \sum\nolimits_{k} \left(C_{xy}^k \cdot S_{xy}^k \right), \|C_{xy}\| = \sqrt{\langle C_{xy}; C_{xy} \rangle}^2,$$

4. Visual quality metrics:

$$PSNR = 10 \cdot \lg \left[\frac{(2^k - 1)^2}{MSE} \right],$$

where k – color depth, MSE – Mean-Squared Error between analyzing images;

$$NHS = \frac{1}{MN} \sum_{q=0}^{2^k-1} |f_C(q) - f_S(q)|,$$

where k – color depth, $f(q)$ – amount of pixels with luminance q;

$$SSIM = \left(\frac{\sigma_{CS}}{\sigma_C \cdot \sigma_S} \right) \cdot \left(\frac{2\bar{C}\bar{S}}{(\bar{C})^2 + (\bar{S})^2} \right) \cdot \left(\frac{2\sigma_C \cdot \sigma_S}{\sigma_C^2 + \sigma_S^2} \right),$$

where:

$$\bar{C} = \frac{1}{MN} \sum_{xy} (C_{sy}), \bar{S} = \frac{1}{MN} \sum_{xy} (S_{sy}),$$

$$\sigma_C^2 = \frac{1}{(M-1)(N-1)} \sum_{xy} (C_{xy} - \bar{C})^2,$$

$$\sigma_S^2 = \frac{1}{(M-1)(N-1)} \sum_{xy} (S_{xy} - \bar{S})^2,$$

$$\sigma_{CS} = \frac{1}{(M-1)(N-1)} \sum_{xy} (C_{xy} - \bar{C}) \cdot (S_{xy} - \bar{S}).$$

Let us consider the DCT-based method of data embedding in DI for illustration the effectiveness of usage the IQM for analysis the fine structure of steganograms. The initial container and steganogram, which are formed by different embedding levels, are shown at Figure 1; corresponding values of IQMs are represented in Table 2.

Table 2. The values of image quality metrics between initial container and formed steganogram by using of DCT-based method (Blue color channel)

Metric	Initial container	10% embedding level	30% embedding level
MD	0	47	143
MSE	0	2.838	14.462
IF	1	0.99955	0.99769
NSMD	0	11374569	56078465
NSPD	0	55.779	127.72
NCC	1	0.99996	0.999244
CD	0	0.0073	0.0229
MAD	1	0.00674	0.019567
PSNR	∞	43.6	36.5
NHS	0	63.231	263.945
SSIM	1	1	0.99851

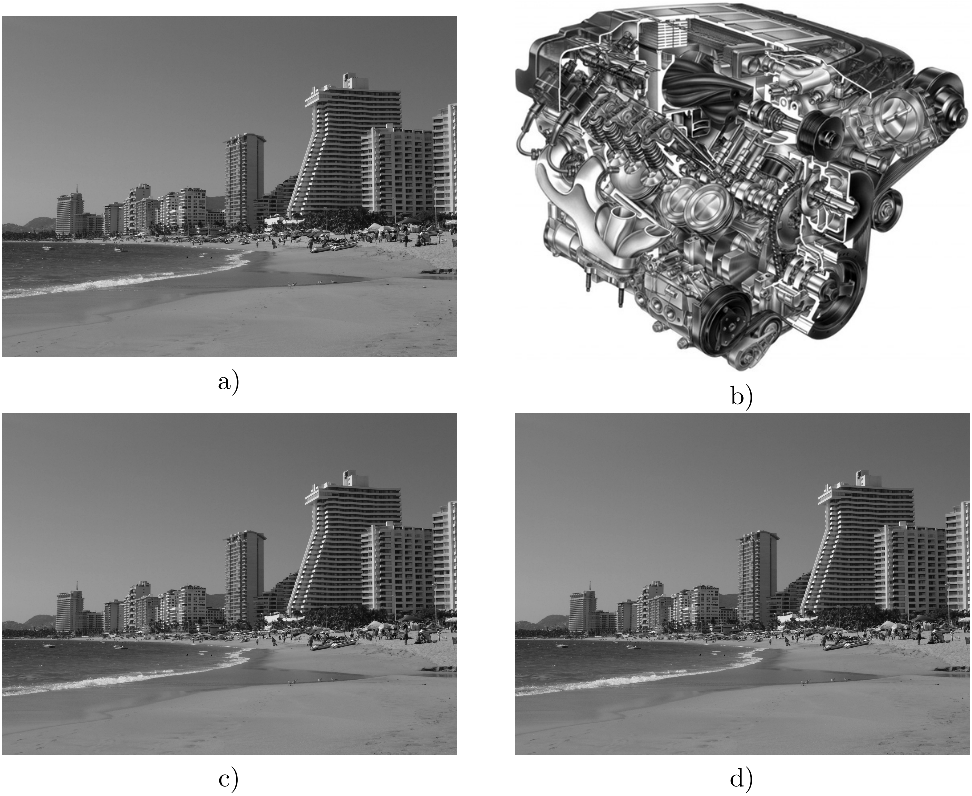


Figure 1. Data embedding in digital image with usage of DCT-based method (Blue color channel, differential parameter $D = 1$): a) initial container; b) secret message. Formed steganogram : c) 10% embedding level; d) 30% embedding level.

As we can see the values of IQM are significantly distinguished from corresponding values for initial container, although the initial container and formed steganogram is visually practically identical.

Results

The analysis of data embedding methods is produced with usage of test packet with 100 DI. The images are divided into 2 groups (with high and low level of detailing) according to expert's conclusion. The parameters of DI and steganodata are represented at Table 1.

The parameters of steganographic methods are chosen in experimental way – before the appearance the visual distortion of images (upper bound) and before the loss of embedding data in the "noise" of DI in frequency domain (lower bound). The obtained parameters of methods:

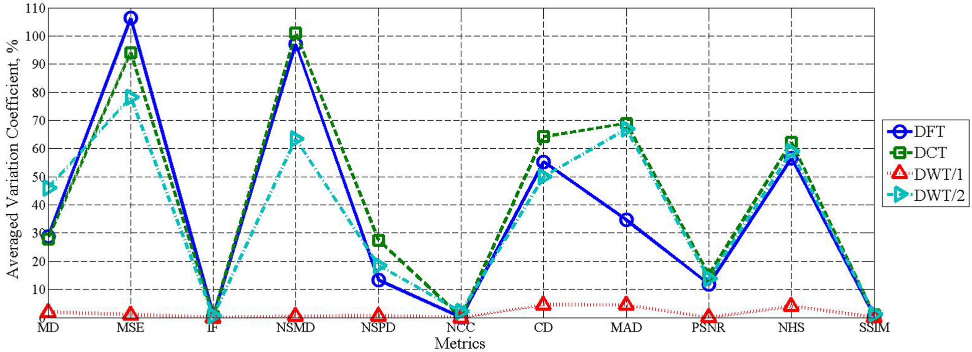
- DFT – scaling parameter $K_S \in \{1; 10; 100; 1000\}$;

- DCT – differential parameter $D \in \{1; 2; 3; 4\}$;
- DWT/1 – size of block $N \in \{16; 20; 24; 28\}$;
- DWT/2 – alpha blending parameter $\alpha \in \{0.02; 0.04; 0.06; 0.08\}$.

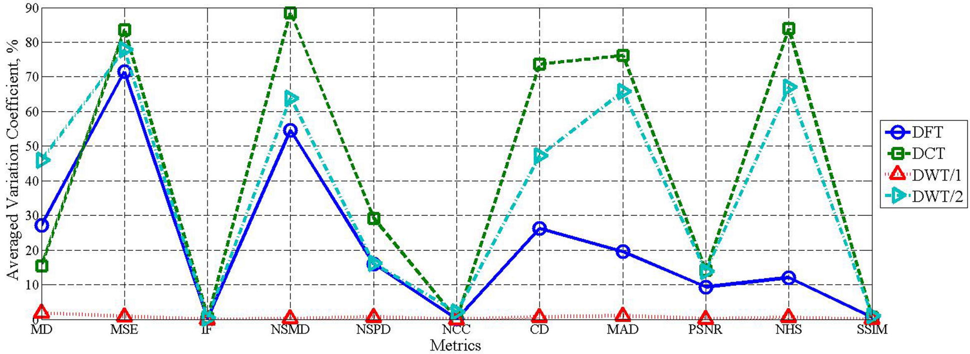
The embedding levels are changed from 10% to 90% with step 20%.

For analyzed embedding methods are computed the variation coefficient, maximum and minimum value of IQMs. The obtained maximum and minimum values for difference image metrics are depended indirectly on the test set of used digital images DI. In consequence of this is used the variation coefficient, which gives opportunity to evaluate the relative degree of image metrics values dispersion by data embedding and is independent of sets the test DI.

The averaged variation coefficients for each group of digital images are represented at Figure 2:



a)



b)

Figure 2. The averaged variation coefficients of separate image quality metrics for groups with: (a) – low detailed digital images; (b) – high detailed digital images.

According to obtained results is established the following:

1. The IF, NCC, PSNR and SSIM metrics characterize the least "sensitivity" to data embedding into frequency domain of DI. It can be explained by

"integral" character of such metrics;

2. The significant distortion of image amplitude spectrum and relatively small changes the image phase spectrum is conditioned by the "mechanism" of data embedding in FD – the separate bit of secret message is embedded by changing only the amplitude of specified element the spectrum without alteration the corresponding phase;
3. The Czenakowski Distance and Mean Angular Difference metrics allow revealing the fact of data hiding with high precision. Specified fact is explained by specific character of such metrics – integral evaluation of image distortion at the all color planes, instead of assessment the distortion on specified color planes, which is characterized for another examined metrics. Also relatively significant values of variation coefficient for CD and MAD metrics indicate that the image's color hue is changed by data embedding;
4. Visually negligible alteration of image by data embedding leads at the same time to significant changes of distribution the pixels luminance, which is clearly reproduced the high values of NHS metric. The considerable changes of pixel's luminance distribution also point out to the change of image's brightness;
5. The method DWT/1 is characterized the least values of each examined metrics in comparison with another analyzed approaches of data hiding. It is explained by using the Integer Wavelet Transform for secret message embedding, which allows to reconstruct the image with minimum alteration.

Conclusion

On the basis of conducted analysis is made the conclusion that data embedding in frequency domain of digital images leads both to alteration the degree of correlation between color planes and change the distribution of pixel's luminance. Usage of specific image quality metrics (Czenakowski distance, Mean Angular Difference and Normalized Histogram Similarity) gives us opportunity to reveal mentioned image distortion and, correspondingly, increase the effectiveness of passive attacks on steganographic system.

Also is established that applying of the most wide spread metrics (e.g. Normalized Cross-Correlation, Peak Signal-to-Noise Ratio) does not allow correctly evaluate the influence of embedding on the container due to their "integral" character. Therefore, for increasing the accuracy of assessment the distortion of image fine structure by data embedding it is proposed to use the groups of versatile image quality metrics – spatial distortion metrics, spectral distortion metrics, correlation characteristics and visual quality metrics.

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