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ADAPTIVE WAVELET SYNTHESIS FOR IMPROVING DIGITAL IMAGE WATERMARKING

Abstract Discrete Wavelet Transform is one of the most popular tools of digital signal processing. Many different wavelet functions have been proposed so far, however there is no wavelet that would be the most suitable for every task. Therefore a method allowing to adaptively synthesize the most suitable wavelet for a given task must be developed. In this paper a general outline of such method will be discussed. A concept of tools used for analysis of adaptive wavelets will be presented.

Keywords Wavelets, Artificial Intelligence, Image Processing

1. Introduction

The Discrete Wavelet Transform (DWT) became one of the most popular tools in the area of digital signal processing during the last two decades. So far different wavelet families have been proposed, such as Daubechies, Coiflet, Morlet or Mexican hat wavelets [1, 2]. Each of these wavelet functions has its unique properties, making some wavelets more suitable for particular tasks than others. This raises a problem of selecting the best wavelet for a particular task, which leads to a question: does there exist a wavelet that would be the best for the given task, but has not been proposed yet? To provide a general answer to this question a method for automatic adaptive synthesis of wavelets should be developed.

The first step towards wavelet adaptation is parameterization of wavelet filter coefficients. Many such parameterizations have been proposed so far [3,4,5,6]. In papers by Rieder et. al [15] and Vaidyanathan [16] a two channel perfect reconstruction finite impulse response filter was implemented using a parameterized lattice structure. A crucial element in these methods was the optimal selection of parameters' values, which was done using well-known numerical optimization methods. In general, filters (including wavelet filters) have to be adapted for a particular application in mind, and therefore optimality criteria have to be defined. These criteria depend on the problem being solved. That problem is presented below.

During the last 15 years, the Internet has given a rise to the problem of extensive copyright violation. Digital data can be easily copied from one computer to another. It is very hard to prove one's ownership of a particular digital work, e.g. image. As a solution to that problem digital data watermarking [7] was created. In this paper digital image watermarking will be discussed. The concept of that method is to embed additional data into the digital image. This additional data – a watermark – is used to prove the ownership of the image. Therefore a watermark should be impossible to remove without damaging the image beyond usability. Moreover, embedding the watermark shouldn't alter the image significantly, as not to interfere with the normal image usage. In the recent years digital watermarking in the wavelet transform domain has gained much popularity. This is caused by the good time–frequency localization properties of the Discrete Wavelet Transform (DWT), which allows to embed a watermark only in the selected regions and frequencies of an image. So far, the authors of the watermarking algorithms have been arbitrarily choosing the wavelet used for image decomposition. Some works have been presented, that introduce a concept of wavelet filter parameterization to improve the digital watermark security – e.g. in paper by Dietl et al. [14] random selection of parameters was proposed to increase the watermark robustness against attacks.

In this paper we discuss a concept of parameterizing wavelet filters using orthogonal lattice structure and performing adaptive parameter selection to adapt the wavelet and thus increase the watermark embedding robustness (sepearability and resistance to attacks) and watermarked image fidelity (quality of the watermarked image). In the previous research it was already demonstrated, that such adaptation is possible and can be carried out using the genetic algorithm approach [8, 9].

This paper is organized as follows. Wavelet filter parameterization using the orthogonal lattice structure is presented in Section 2. The theory behind the digital image watermarking in the wavelet transform domain is presented in Section 3. Section 4 discuses the details of genetic approach to optimization of the lattice structure parameters and presents the optimality criteria that will be used for the wavelet synthesis. Section 5 presents a concept of tools for studying the relation between the wavelet filter parameters and the effectiveness of synthesized wavelets. A summary and the direction of future research are given in Section 6.

2. Orthogonal wavelet transform

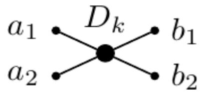

Fig 1. Base operation

Orthogonal lattice structure is a computational scheme introduced in [10] and discussed in more detail in [11]. It is based on two point base operations (presented in Figure 1), that can be viewed as a 2x2 matrix multiplication:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = D_k \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \text{ where } D_k = \begin{bmatrix} w_1^{(k)} & w_2^{(k)} \\ w_2^{(k)} & -w_1^{(k)} \end{bmatrix}, \quad (1)$$

It is assumed, that D_k is orthogonal:

$$D_k \cdot D_k^T = I, \quad (2)$$

which means that weights $w_1^{(k)}$ and $w_2^{(k)}$ fulfil the following conditions:

$$w_1^{(k)} w_2^{(k)} - w_1^{(k)} w_2^{(k)} = 0, \quad (3)$$

$$(w_1^{(k)})^2 + (w_2^{(k)})^2 = 1. \quad (4)$$

Condition (3) is of course always satisfied, which is ensured by the definition of the D_k base operation. Equation (4) is explicitly satisfied, when the following substitutions are assumed [12]:

$$\mathrm{w}_1^{(k)} = \cos(\alpha_k)\,,\ \mathrm{w}_2^{(k)} = \sin(\alpha_k)\,. \tag{5}$$

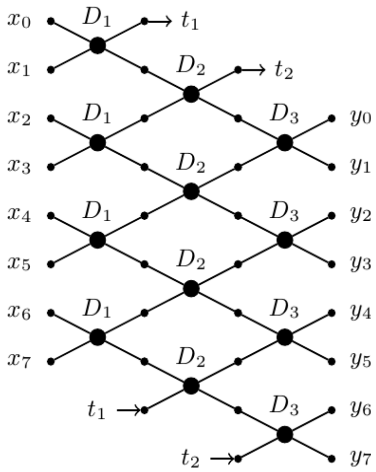

Fig 2. Lattice structure implementing 6-tap transform

Base operations are composed into layers (see Figure 2). Orthogonal lattice structure is composed of *K/2* stages, each containing D_k operations repeated *N/2* times, where *K* and *N* are the lengths of the wavelet filter's impulse response and of a processed signal respectively. On each stage of the lattice structure, elements of the signal are processed in pairs by D_k base operations. After each stage, base operations are shifted down by one and a lower input of the last base operation in the current stage is connected to the upper output of the first base operation in the preceding stage (t_1 and t_2 in Fig. 2). Upper outputs of base operations in the last layer (y_0, y_2, y_4 and y_6 in Fig. 2) correspond to the low–pass filter signal and lower outputs (y_1, y_3, y_5 and y_7 n Fig. 2) correspond to the high–pass filter signal.

A lattice structure, with base operations fulfilling conditions (2)–(4), is able to implement a wavelet filter bank that fulfils conditions of wavelet decomposition, assuming that the following constraint imposed on the α_k angles holds true [17]:

$$\underset{n\in Z}{\exists}\sum_{l=1}^{L/2}\alpha_l=\frac{\pi}{4}+\left[\left(\frac{L}{2}-1\right)\bmod 4\right]\cdot\frac{\pi}{2}+2n\pi\,. \tag{6}$$

To ensure that the above equation always holds true, the following representation has been introduced [15]:

$$\begin{gathered}\alpha_1=\gamma-\varphi_1\\ \alpha_i=(-1)^i(\varphi_{i-1}-\varphi_i),\ \text{for}\ i=2,\ldots,\frac{L}{2},\\ \alpha_{L/2}=(-1)^{L/2}\varphi_{L/2-1}\end{gathered} \tag{7}$$

where γ is the desired sum of angles and is determined depending on the number of layers in the orthogonal lattice structure. Such a representation assures, that condition

$$\sum_{l=1}^{L/2}\alpha_l=\gamma\,, \tag{8}$$

is always fulfilled. It also means that orthogonal lattice structure, consisting of $L/2$ layers, can be represented using a set of $L/2-1$ angles $(\varphi_1,\ldots,\varphi_{L/2-1})$, instead a set of $L/2$ angles $(\alpha_1,\ldots,\alpha_{L/2})$.

Wavelet filter bank coefficients are calculated based on the D_k base operations. Wavelet synthesis is performed by adjusting the $w_1^{(k)}$ and $w_2^{(k)}$ parameters of the D_k base operations.

3. Digital image watermarking in the wavelet transform domain

Many digital image watermarking algorithms operating in the wavelet transform domain have been proposed so far. All of these algorithms share a common embedding scheme. The original data is first decomposed using the discrete wavelet transform and the Mallat algorithm for multilevel decomposition of a signal (usually 3 to 5 image decomposition levels are used). The watermark is then embedded in the wavelet coefficients using the selected embedding algorithm. Inverse wavelet transform is applied to reconstruct the watermarked image. To extract the watermark, image decomposition using discrete wavelet transform must be performed on the watermarked image. Watermark extraction algorithm is then used to recover the watermark from the wavelet coefficients. The extracted watermark is then compared to the embedded watermark. If their similarity (in most cases measured as correlation) is large enough, the watermark presence is detected.

The approach proposed in this paper operates on the generic watermark embedding method called E_BLIND [7], but it can also be applied to any other method of digital image watermarking in the wavelet transform domain. In the E_BLIND algorithm the watermark w_r is a random sequence of N integer numbers of the set $\{-1, 1\}$. Multilevel Discrete Wavelet Transform of the image is performed using Mallat's decomposition algorithm. N largest wavelet coefficients from all three detail sub–bands on third level of image decomposition are selected. This means, that the watermark is embedded in the mid–frequencies of an image. The watermark is embedded in the selected coefficients using formula

$$c_w = c_0 + \alpha |c_0| w_r\,, \tag{9}$$

where c_0 are the selected wavelet coefficients, α is the embedding strength, w_r is the watermark and c_w are the watermarked wavelet coefficients.

To extract the watermark, watermarked image has to be decomposed using the Mallat's algorithm with the same number of decomposition levels as was used for watermark embedding. Location of the watermarked coefficients must be known. Watermark is detected by computing the normalized correlation between the watermarked wavelet coefficients and the original watermark according to the formula

$$C = \frac{1}{N-1} \sum_{k=1}^{N} \frac{(c_w(k) - \overline{c_w})(w_r(k) - \overline{w_r})}{\sigma_r \sigma_w}\,, \tag{10}$$

where N is the length of the watermark, c_w denotes the watermarked coefficients, $\overline{c_w}$ is the mean value of the watermarked coefficients, w_r denotes the embedded watermark, $\overline{w_r}$ is the mean value of the embedded watermark, σ_c and σ_w are standard deviations of the watermarked coefficients and the watermark respectively. Presence or absence of the watermark is usually determined with a threshold τ. If the correlation C is greater than τ then the watermark is present, otherwise it is absent. It is therefore important to maximize the correlation.

4. Wavelet adaptation using the genetic algorithm

When the base operations of a lattice structure are modified, the output signal from the lattice structure changes. This signal can be rated in terms of its fitness in respect to some quality criteria. In the digital image watermarking, there are three contradicting fitness criteria:

- Correlation between the extracted watermark and the random watermarks should be minimized, while maximizing the correlation between the extracted watermark and the embedded watermark (separability),

- Visual difference between the original image and the watermarked image should be minimized (fidelity),

- Watermark resistance against attacks should be maximized (robustness).

This turns the problem of mother wavelet synthesis using lattice structure into a multi-objective optimization problem, which can be solved using the genetic algorithm approach. The author proposes an algorithm based on Simple Genetic Algorithm and expanding it to use Evolution Strategies. Below is the outline of proposed genetic algorithm:

- *initialize random population P of μ individuals*

- *FOR k = 1 TO iterations_count DO*
- *evaluate fitness of individuals in population P*
- *create temporary population T containing λ individuals selected from population P*
- *perform crossover and mutation on individuals in population T*
- *evaluate fitness of individuals in population T*
- *select μ individuals to form new population P*
- *END FOR*
- *display the best individual in population P*

The stop condition is reaching the maximum number of iterations. Individuals in the genetic algorithm are represented as a set of binary coded $(\varphi_1,\ldots,\varphi_{L/2-1})$ angles, representing the orthogonal base operations (according to equations (1), (4) and (6)). Each φ_k angle is binary coded on a chromosome ch_k using m bits. This means that it can be treated as an integer from range $[0,\ 2^m)$. To convert chromosome ch_k to φ_k angle the following formula is applied:

$$\varphi_k = 2\pi \frac{ch_k}{2^m} = \frac{ch_k \cdot \pi}{2^{m-1}} \,. \tag{11}$$

It assures that φ_k angle falls into range $[0,2\pi)$. After all the φ_k angles have been calculated, they are converted to α_k angles using equation (6). These angles are used to calculate the base operation according to equations (4) and (1). After the base operation are calculated they can be used to perform the wavelet transform in the watermark embedding algorithm.

To evaluate individual's fitness in terms of criterion 1 a set of random watermarks must be generated. First, the normalized correlation between the extracted watermark and the embedded watermark is calculated. Then the normalized correlation between the extracted watermark and the random watermarks is calculated. The fitness of *i*–th individual in terms of the first criterion is calculated using the formula:

$$F_i^{(1)} = \min_j (C_e^{(i)} - C_{rj}^{(i)}) , \tag{12}$$

Where $C_e^{(i)}$ is the normalized correlation between the extracted watermark and the watermark embedded using the *i*-th individual (filter) and $C_{rj}^{(i)}$ is the normalized correlation between the extracted watermark and the *j*-th random watermark for *i*-th individual.

Fitness in terms of the second optimality criterion is calculated using the standard image similarity assessment method – PSNR:

$$F_i^{(2)} = 10 \cdot \log_{10} \frac{255^2}{MSE} , \tag{13}$$

where MSE is the Mean Square Error between the watermarked image and the original image:

$$MSE = \frac{1}{NM} \sum_{i=1}^{M} \sum_{j=1}^{N} [O(i,j) - W(i,j)]^2 , \tag{14}$$

where $O(i,j)$ and $W(i,j)$ are pixel values of original and watermarked image respectively, N and M are image dimensions.

The optimality in terms of the third criterion isn't assured by directly computing individual's fitness. Instead, after the watermark is embedded in the image a certain type of image attack (scaling, compression, low-pass or median filtering, etc.) is performed on the watermarked image before the watermark is extracted. Then the fitness $F_i^{(1)}$ is calculated. The performed attack influences that fitness, thus individuals, that have high fitness, despite the attack performed on the image, are discovered.

As the method for multi-objective optimization the Global Optimality Level is used [13]. The first step is determination of the maximal and minimal value in the population of each partial fitness:

$$F_{\min}^{(j)} = \min_i \{F_i^{(j)}\}$$
$$F_{\max}^{(j)} = \max_i \{F_i^{(j)}\}, \tag{15}$$

where i and j are the indices of individuals and partial fitness respectively. The final fitness F_i of an individual is calculated using the formula:

$$F_i = \min_j \left\{ \frac{F_i^{(j)} - F_{\min}^{(j)}}{F_{\max}^{(j)} - F_{\min}^{(j)}} \right\}. \tag{16}$$

This equation means, that every partial fitness of an individual is normalized to fit into range [0,1]. The worst partial fitness is then selected as the final fitness of an individual. Such an approach promotes individuals that ensure both the good image quality and the resistance to the attacks.

To create the temporary population T (step 4 in the algorithm outline), λ individuals are selected from the base P population containing μ individuals, where $\lambda > \mu$. Either the Tournament Selection or the Roulette Wheel Selection can be applied. Individuals in the temporary population are modified using two genetic operators: the crossover operator and the mutation operator. These operators create new individuals (solutions) within the population T. Having the original population P and the temporary population T, the new population P must be created. Author proposes to use the evolution strategies for that purpose: $(\mu + \lambda)$ strategy and (μ, λ) strategy. In the $(\mu + \lambda)$ strategy, the new population P is created by selecting μ fittest individuals from both the parents (population P) and the offspring (population T). This strategy assures stability of the optimization process – if the new individuals from population T are less fit than in the original population, they will not be placed into the next generation (the parents are copied to the next generation if they have higher fitness). This, however, may lead to dominating the population by fit individuals early in the optimization process, and thus lead to premature convergence. In the *(μ, λ)* strategy the original population *P* is discarded and the new population *P* is created by selecting μ fittest individuals from the *T* population. Experiments have shown, that if no evolution strategy is applied, then unfit individuals are not eliminated from the population, which leads to destabilization of the optimization process.

Genetic algorithms are an efficient method of global optimization for solving complex tasks and have proven to be an effective method of wavelet synthesis for improving digital image watermarking [9].

5. Tools for adaptive wavelet synthesis

So far there have been no tools that would allow to adaptively synthesize wavelets nor there have been tools to study the influence of wavelet parameters on the watermarking process. Therefore the author of this paper proposes to create two separate tools to aid the research of adaptive wavelets and their influence on the digital image watermarking process. These tools are discussed below.

5.1. Wavelet Plotter

Wavelet Plotter will be the basic tool to study the influence of orthogonal lattice structure parameters on the digital image watermarking process. Its basic functionality is plotting of the scaling function based on the parameters given by the user (the parameters for Daubechies 4, Daubechies 6 and Daubechies 8 wavelets are stored in the program). Coefficients of the filter will be displayed in the program and the plot precision can be adjusted. The second of the Wavelet Plotter's functionalities is embedding the digital image watermark. User will be able to select the image file as well as the embedding parameters (watermark amplitude, watermark length etc.). Watermark embedding method will be E_BLIND, although it will be easy to extend the program with other watermarking algorithms. The watermarked image will be displayed, so the user will be able to visually rate the watermarking fidelity. Peak Signal-to-Noise Ratio

(PSNR) of the watermarked image will also be displayed to the user. Beta version of the application in Polish language is presented in the Figure 3.

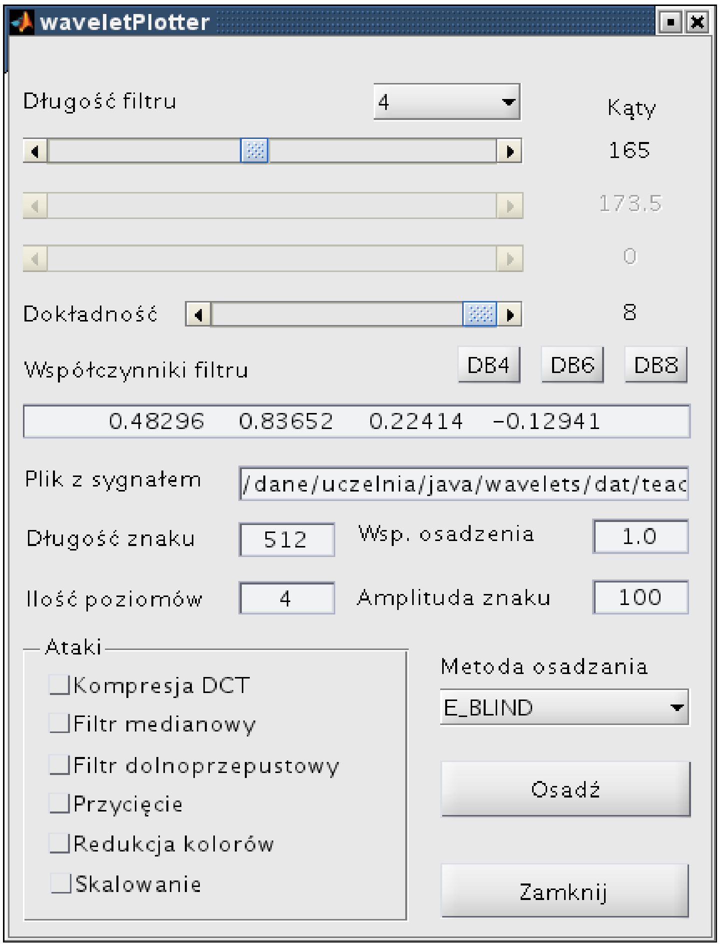

Fig 3. Wavelet Plotter (beta version)

5.2. Adaptive Wavelet Synthesizer

While Wavelet Plotter allows to manually adjust the wavelet parameters, the second of the proposed tools will perform automatic adaptive wavelet synthesis using a genetic algorithm. User will be able to adjust the parameters related with the wavelet decomposition (filter length, number of wavelet analysis levels), the genetic algorithm (number of algorithm's iterations, representation precision, crossover and mutation probability, selection method, crossover method, evolutionary strategy, population size) and the watermarking process (watermark length and amplitude, embedding strength, embedding algorithm). It will be also possible to perform various kinds of attacks on the watermarked image (DCT compression, median and low–pass filtering, scaling, colour depth reduction) to synthesize wavelets that will make the watermark resistant to these attacks. As a final result of the program, user will be provided with the low–pass and high–pass filter coefficients of the best synthesized wavelet. Moreover, the effectiveness of the synthesized wavelet will be automatically compared to the Daubechies family wavelet in terms of image fidelity, correlation and watermark separability. The concept version of user interface for Adaptive Wavelet Synthesizer is presented in Figure 4.

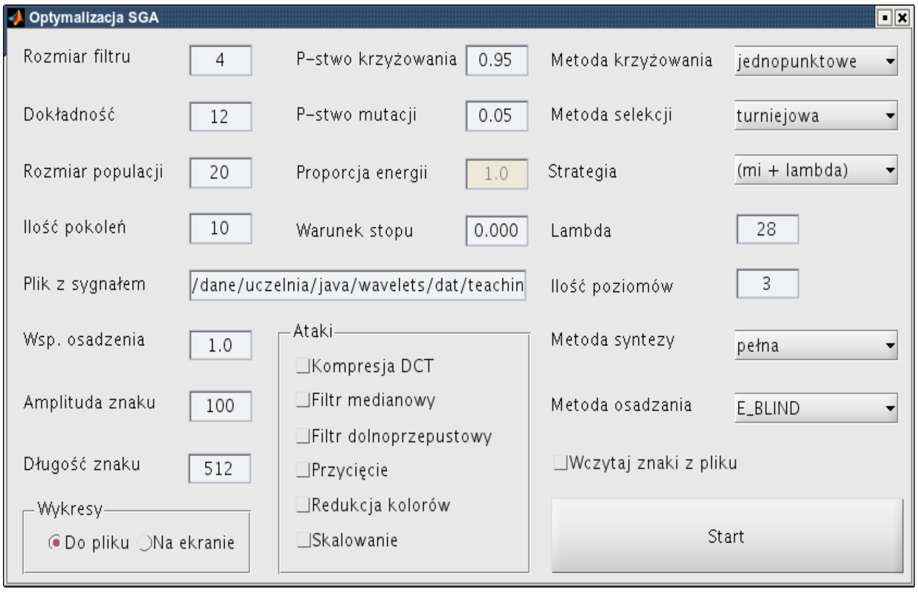

Fig 4. Adaptive Wavelet Synthesizer (concept)

6. Summary

In this paper an orthogonal lattice structure used for wavelet parameterization was presented. The problem of improving digital image watermarking effectiveness was discussed. During the earlier research it was shown, that adjusting the wavelet function can significantly improve the watermarked image fidelity and the watermark separability. Two applications have been proposed to aid the scientists researching the adaptive wavelet synthesis. First of the applications will allow to manually adjust wavelet parameters to study the particular wavelet function. Second of the applications will automatically synthesize adaptive wavelets to study how the watermark length, the embedding strength and the attacks performed on the image influence the coefficients of synthesized wavelets.

As part of the future research both applications will be implemented in the Matlab environment. Created programs will be used to further study the practical aspects of digital image watermarking improvement. Presented application concepts may be further expanded, e.g. different image quality assessment methods or meta algorithms for auto selecting parameters of the evolutionary algorithm may be implemented. Moreover, the theoretical background of proposed lattice structure will also be studied in more detail (first part of research has already been published in [17]).

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