A NEW DWT-SVD BASED PERCEPTUAL FIDELITY METRIC FOR QUALITY ASSESSMENT OF WATERMAKING SCHEMES

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ABSTRACT

A new DWT-SVD perceptual fidelity metric for the evaluation of watermarking schemes is introduced in this paper. A widely used Human Visual Model in the Discrete Wavelet Transform domain is employed by the metric to account for the frequency sensitivity, and the local luminance and contrast masking effects of the human eye. A relationship between the visual model in the DWT domain and the modification of the wavelet coefficients singular values is derived. Subjective experiments are used to validate the proposed metric, and its performance is compared to several state-of-the-art perceptual image distortion metrics. The paper focuses on Image Adaptive Watermarking methods in the Discrete Wavelet Transform Domain since they yield better results regarding robustness and transparency than other watermarking schemes.

1. INTRODUCTION

Digital Watermarking refers to techniques that imperceptibly embed information (the watermark) into the original data in such a way that always remains present and detectable. One of the main requirements that should be met by any watermarking technique is the *perceptual transparency* that refers to the property of the watermark of being imperceptible in the sense that humans can not distinguish the watermarked images from the original ones by simple inspection [1], [6].

The assessment of watermarked image fidelity is one of the key aspects in the evaluation of image watermarking insertion methods. Basically, the fidelity is a measure of the similarity between the images before and after the watermark insertion. Many works exist in the literature dealing with quality assessment mainly focused on compression applications. Nevertheless, visual quality assessment should include special requirements that depend on the application context. An extended review of image quality assessment techniques in watermarking and data hiding applications can be found in [11].

Generally speaking, image fidelity assessment can be performed following two different approaches: subjective evaluation and objective evaluation. In the subjective assessment a number of observers are asked to rank the distortion of the images in a given scale and a Mean Opinion Score (MOS) is obtained. This type of evaluation is time consuming and it can be influenced by experimental conditions (such as lighting, monitor characteristics, etc.), and lack of motivation and mood of the participants. On the other hand, in the objective assessment approach, a distortion metric is mathematically defined and computed from the original and watermarked images, and is then used to quantify the watermarked image fidelity in an automatic way, without the involvement of human beings. This classification of the different approaches for image fidelity assessment is considered within the framework of the so-called *full reference image quality evaluation* techniques, where both the original and the distorted images are assumed to be available for the computations.

Among the objective image quality metrics, two different classes can be distinguished: metrics based only on the characteristics of the image, usually called *pixel-based metrics*, and metrics that take also into account perceptual characteristics of the Human Visual System (HVS), which for this reason are called *perceptual quality metrics*. Within the first class the widely used mean squared error (MSE), the peak signal to noise ratio (PSNR), the root mean squared error (RMSE), the mean absolute error (MAE), the signal-to-noise ratio (SNR), the Universal Image Quality Index (UQI) proposed in [23], and the metric based on Singular Value Decomposition (SVD) introduced in [21], can be mentioned. Within the second class, the structural similarity metric (SSIM) introduced in [22], and the Komparator metric proposed in [12], can be mentioned. As pointed out in [8], pixel-based metrics do not correlate well with human visual distortion perception. The same conclusion is drawn in [17], where a comparison of several perceptual and non perceptual metrics in the framework of image watermarking is carried out.

In this paper, a new perceptual metric for fidelity evaluation of watermarked images is presented and validated through subjective tests. The metric resorts to a widely used perceptual model of the HVS introduced in [25], which takes into account frequency sensitivity, local luminance and contrast masking effects to determine an image-dependent quantization matrix. This model provides the maximum possible quantization error in the DWT coefficients which is not perceptible by the HVS. A relationship between these maximum quantization errors in the DWT domain and the maximum variation of the wavelet coefficients's singular values is derived. For the purposes of comparison the HVS model introduced in [2], which is a modification of the model in [13], is used to build a similar metric. The performance of the proposed metrics are compared with two state-of-the-art perceptual fidelity metrics, namely, the Komparator metric introduced in [12], and the SSIM metric introduced in [24].

A wide variety of watermarking schemes have been proposed in the literature. Among the different approaches, the ones in the Discrete Wavelet Transform domain that are adapted to the particular image, called hereafter Image Adaptive Discrete Wavelet Transform (IADWT) watermarking schemes, have proved to have better performance regarding robustness against attacks and fidelity. For this reason, IADWT watermarking schemes will be considered in this paper. In particular, the IADWT schemes introduced in [20] and in [7] will be employed for the evaluation of the proposed fidelity metric.

The rest of the paper is organized as follows. In section 2, a brief review of the Singular Value Decomposition and its application in image processing is presented. In section 3, the new perceptual fidelity metric based on DWT and SV decompositions is introduced. The general conditions for the subjective tests used to validate the different fidelity metrics are described in section 4. The results of the subjective evaluation applied on two IADWT watermarking schemes, together with the results of the proposed objective metric are presented in section 5. Finally, some concluding remarks are given in section 6.

2. SINGULAR VALUE DECOMPOSITION

Any real matrix A can be decomposed into a product of three matrices as $A = U\Sigma V^T$, where U and V are orthogonal matrices ($U^TU = I, V^TV = I$), and $\Sigma = diag(\sigma_1, \sigma_2, \ldots \sigma_N)$. The diagonal entries σ_i of Σ are called the singular values of A, while the columns of U and the columns of V are called the left and right singular vectors of A, respectively [9]. This decomposition is known as the Singular Value Decomposition (SVD) and has many applications in signal and image processing. In particular, in the area of image processing, the SVD of an image is an optimal decomposition, in the sense that most of the signal energy is concentrated in few coefficients (singular values). In addition, the SVD has properties of stability, proportion invariance and rotation invariance.

The SVD has also been used in recent years in watermarking applications, see for instance [4], [5], [15], [18], [19], [26], [27] where different watermarking schemes based on modification of the singular values are presented. More recently, the SVD has been used in combination with the DWT decomposition in different watermarking schemes. For instance, in [3] a semi-blind reference watermarking scheme for copyright protection using gray scale logos as watermarks is presented. For the watermark embedding, the original image is transformed using DWT, a reference image is obtained, and then the watermark is embedded into the reference image by modifying its SVs, using the SVs of the watermark. In [14], a hybrid DWT-SVD watermarking scheme that considers Human Visual properties is introduced. The embedding is done by DWT decomposing the host image into four subbands, applying SVD to each subband, and then modifying the SVs using the SVs of the watermark. The watermark strength is determined by the HVS model proposed in [13].

3. DWT-SVD METRIC PROPOSAL

In this section, a new image fidelity metric based on DWT and SVD decompositions is introduced. The metric benefits from the advantages of the Discrete Wavelet Transform Decomposition regarding space-frequency resolution and of the Singular Value Decomposition of an image regarding the compactness of the representation of the signal energy in a few coefficients. The metric resorts to a widely used perceptual model of the HVS introduced in [25], which takes into account frequency sensitivity, local luminance and contrast masking effects to determine an image-dependent quantization matrix, which provides the maximum possible quantization error in the DWT coefficients which is not perceptible by the HVS. These values are the so-called Just Noticeable Difference (JND) thresholds. It should be noted that the methodology described bellow is flexible enough to accommodate the use of any HVS model in the DWT for the computation of the JND thresholds. In particular the model in [2] was also used in this paper.

In a first stage, a 1-level DWT decomposition is performed for both the original and the watermarked images, using the biorthogonal 7/9 wavelet [16], resulting in the coefficient matrices C_{LL}, C_{LH}, C_{HL}, C_{HH} for the original image and C^w_{LL}, C^w_{LH}, C^w_{HL}, C^w_{HH} for the watermarked image. Here, the subindexes LL, HL, LH and HH indicate approximation, and vertical, horizontal and diagonal details, respectively.

The Singular Value Decomposition of each coefficient matrix is then performed, resulting in four singular values matrices for each subband of the original image, namely Σ_{LL}, Σ_{LH}, Σ_{HL} and Σ_{LL}, and four singular values matrices for each subband of the watermarked image, namely, Σ^w_{LL}, Σ^w_{LH}, Σ^w_{HL} and Σ^w_{LL}. Then, the absolute difference of the singular values matrices for each subband is computed according to

$$\Delta\Sigma_i \triangleq |\Sigma_i - \Sigma_i^w|, \qquad i = LL, LH, HL, HH \tag{1}$$

The watermark in the watermarked image will be imperceptible if the variation of the wavelet coefficients associated to the singular value differences in (1) do not exceed the JND thresholds of the DWT domain HVS model. An SVD decomposition of the DWT perceptual thresholds for the ith-subband, JND_i, permits to obtain the singular value perceptual thresholds as follows,

$$JND_i = U_i \Sigma_{JND_i} V_i^T \Rightarrow \Sigma_{JND_i} = U_i^T JND_i V_i \ , \tag{2}$$

with $i = LL, LH, HL, HH$.

A variation of the singular values of a specific subband will then be perceptible if the difference $\Delta\Sigma_i$ in (1) exceeds the singular value perceptual thresholds Σ_{JND_i}.

A matrix $Thresh(\Delta\Sigma_i)$ can be defined from $\Delta\Sigma_i$ by zeroing the entries which are below the perceptual thresholds Σ_{JND_i}, and then, a single value of distortion for each subband can be defined as follows:

$$d_i \triangleq \frac{\|Thresh(\Delta\Sigma_i)\|_F}{\|\Sigma_i\|_F}, \qquad i = LL, LH, HL, HH \tag{3}$$

where $\|\cdot\|_F$ stands for the Frobenius norm of a matrix, and the normalization by $\|\Sigma_i\|_F$ has been performed in order for the distortions d_i to be in the range $[0, 1]$.

Finally, to provide a unique parameter quantifying the distortion, a pooling of the four subband distortion measures is needed. An objective fidelity metric can then be defined as the complement of the linear combination of the four distortion measures in (3), *i.e.*,

$$f \triangleq 1 - (k_{LL}d_{LL} + k_{LH}d_{LH} + k_{HL}d_{HL} + k_{HH}d_{HH}), \tag{4}$$

where the coefficients k_{LL}, k_{LH}, k_{HL} and k_{HH} must satisfy the constraint

$$k_{LL} + k_{LH} + k_{HL} + k_{HH} = 1, \tag{5}$$

in order for f to be in the range $[0,1]$.

A schematic representation of the algorithm for the computation of the objective fidelity metric is shown in Fig. 1.

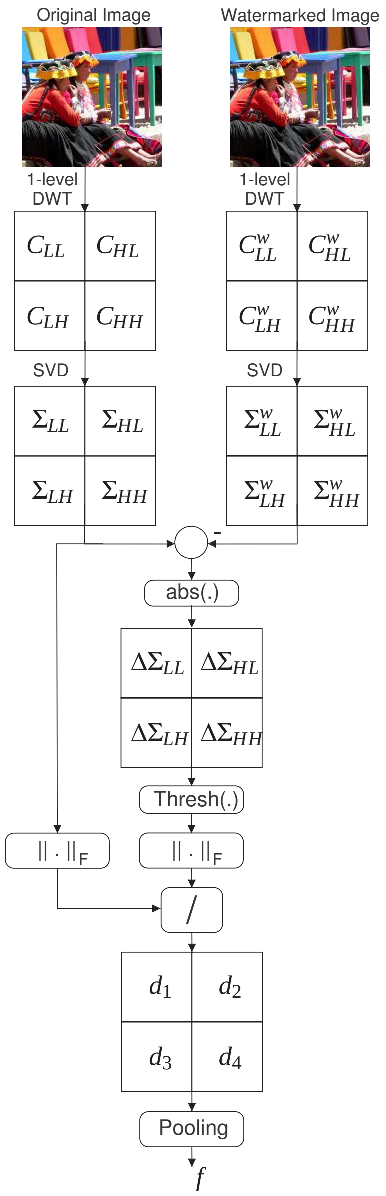

Figure 1: DWT-SVD based image fidelity metric algorithm.

4. METRIC VALIDATION

In this section, the experiments for the subjective validation of the proposed fidelity metric are described.

As pointed out before the straightforward way to assess the fidelity of watermarked images is to run a subjective test. There are standard techniques to perform subjective tests for general image quality assessment. For instance, the Recommendation ITU-R BT.500-11 [10] specifies a methodology for the subjective assessment of still image quality. On the other hand no standards are available for subjective assessment of watermarked image quality. Since watermarked images can be considered as the result of some processing operations (the watermark embedding algorithms) applied to the original image, these general subjective quality assessment techniques could be applied to watermarked images. In this paper, the Double Stimulus Impairment Scale (DSIS) protocol, described in [10], is used. This protocol has also been used by Marini and coauthors in [17] in the same context.

The experiments were carried out in a room designed according to the recommendation ITU-R BT.500-11 [10]. Fifteen non expert observers, with ages from 23 to 33 years, were enrolled to do the test. Fifteen different natural images (including portraits, landscapes, wildlife, etc.) were watermarked using two state-of-the-art Image Adaptive DWT insertion schemes. Namely, the algorithm proposed in [20], and the one introduced in [7]. These techniques in the DWT domain take into account the image characteristics and a model of the Human Visual System to adapt the strength of the watermark to make it imperceptible. These IADWT techniques have also proved to deliver better results, regarding robustness and fidelity, than image independent watermarking schemes.

This setup resulted in 20 min sessions where observers were asked to rate 30 images at an observation distance (D_{obs}) of six times the display size of the images. The original and the watermarked images were displayed side by side on the monitor as shown in Figure 2, and the observers were asked to rate the quality of the marked image compared to that of the original on a scale of five categories, namely 5=Imperceptible, 4=Perceptible but not annoying, 3=Slightly annoying, 2=Annoying, and 1=Very annoying.

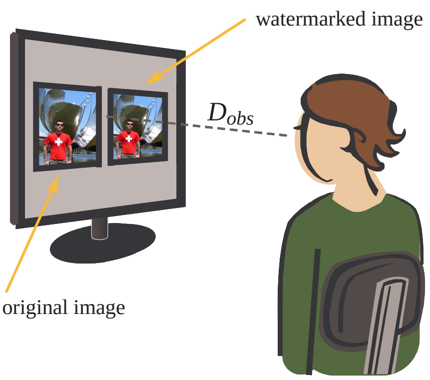

Figure 2: Subjective Experiment Setup.

The results of these experiments are included in section 5.

5. RESULTS

The metric described in Section 3 is used in this section to evaluate the fidelity of the two IADWT watermarking schemes mentioned before. A set of fifteen (256×256) natural color images was used. The complete image data set can be downloaded from the authors's website (http://www.fceia.unr.edu.ar/lsd/mrg/watermark/). Four of the images are shown in Fig. 3

Three perceptual image fidelity metrics are considered in this section. Namely, the Komparator metric introduced in [12], the SSIM metric introduced in [24], and the metric introduced in Section 3 with the two different HVS models,

Figure 3: Four images in the database.

namely f_{Watson} for the HVS model in [25] and f_{Barni} for the HVS model in [2].

In order to illustrate which metric provides the best objective assessment of image quality for both watermarking methods, the three metrics are computed and compared to the Mean Opinion Score [1] (MOS) for the fifteen images. The corresponding 97.5 % confidence intervals (*CI*) were also calculated to specify intervals of values with the highest likelihood of containing the true value of the general MOS. These intervals, centered in the MOS, are shown as blue solid boxes in Fig. 4. The metric f_{Watson} introduced in this paper is denoted with green triangles, the SSIM values with orange squares, while the Komparator values with brown circles. The values in Fig. 4 are normalized in the range $[1,5]$. The metric f_{Barni} is not included in Fig. 4 for the sake of clarity.

The number of points that fall outside the confidence intervals and the average distance (δ) of each metric to the MOS were calculated for both Watermarking algorithms and the corresponding values are shown in Table 1. From Fig. 4 and Table 1, it can be observed that the metric f_{Watson} is the one that best fits the subjective results, although the Komparator and the f_{Barni} metrics give also acceptable results.

Table 1: Performance of the metrics for the IADWT watermarking schemes in [20] and [7].

	IADWT [20]		IADWT$_T$ [7]	
	Points outside *CI*	δ	Points outside *CI*	δ
SSIM	9	0.29	2	0.12
Komparator	3	0.26	3	0.20
f_{Barni}	3	0.29	2	0.15
$\mathbf{f_{Watson}}$	**2**	**0.26**	**1**	**0.13**

[1]The Mean Opinion Score for each image is the average of the scores assigned by all observers.

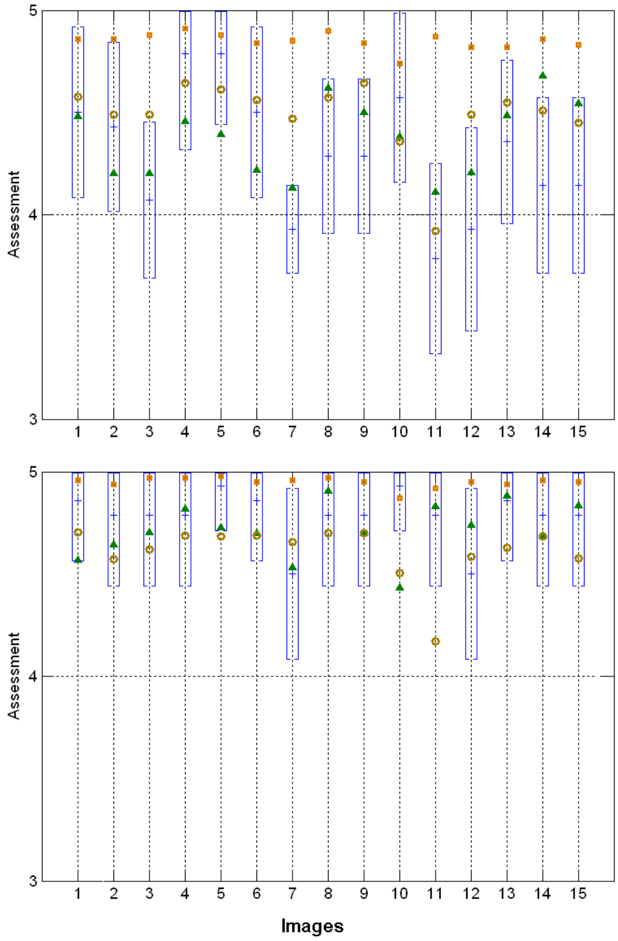

Figure 4: Comparison of Objective and Subjective Assessment for methods IADWT (top) and IADWT$_T$ (bottom). *CI*: Blue solid boxes, f_{Watson}: green triangles, SSIM: orange squares, Komparator: brown circles.

6. CONCLUDING REMARKS

In this paper, a new perceptual metric for fidelity evaluation of watermarked images was presented and validated through subjective tests. The proposed metric resorts to a widely used perceptual model of the HVS, which provides the maximum possible quantization error in the DWT coefficients which is not perceptible by the HVS. A relationship between these maximum quantization errors in the DWT domain and the maximum variation of the wavelet coefficients's singular values was derived in the paper. It was also shown that the proposed metric can be adapted to other HVS models in the DWT domain, like the one in [2], with acceptable performance.

The performance of the metric was compared with two state-of-the-art perceptual fidelity metrics, showing better correlation with the subjective tests for the purposes of quantifying image watermarking fidelity. The experiments were performed using two IADWT watermark insertion algorithms. It is the intention of the authors to test the metric with other watermarking schemes, in particular, with some of the SVD-based algorithms listed in section 2.

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