looks amplitude) of San Francisco Bay. Lee's refined filter tends to overly segment because of the anisotropic behavior of its algorithm in the presence of edges. Meer's filter is similar, but avoids this drawback and is, on the whole, slightly better. Indeed, MLPF appears superior on homogeneous areas, in which the smoothing effect is adequate, and especially on textured regions, in which even fine textures are preserved.

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Multiresolution Watermarking for Digital Images

Chiou-Ting Hsu and Ja-Ling Wu

***Abstract*—In this paper, a multiresolution-based technique for embedding digital "watermarks" into images is proposed. The watermarking technique has been proposed as a method by hiding secret information into the images so as to discourage unauthorized copying or attesting the origin of the images. In our method, we take advantage of multiresolution signal decomposition. Both the watermark and the host image are composed of multiresolution representations with different structures and then the decomposed watermarks of different resolution are embedded into the corresponding resolution of the decomposed images. In case of image quality degradation, the low-resolution rendition of the watermark will still be preserved within the corresponding low-resolution components of the image. The experimental results show that the proposed watermarking technique results in an almost invisible difference between the watermarked image and the original image, and is robust to common image processing operations and JPEG lossy compression.**

I. Introduction

With the increase of digital media, data distribution is becoming faster, easier, and is requiring less effort to make exact copies. One of the major challenges for intellectual property protection of digital media is to discourage unauthorized copying and distribution [1]. Digital watermarking has been proposed as a way to claim the ownership of the source and owner. To achieve maximum protection, the watermark should be: 1) undeletable; 2) perceptually invisible; 3) statistically undetectable; 4) resistant to lossy data compression; 5) resistant to common image processing operations; and 6) unambiguous.

Various watermarking techniques have been proposed over the years [2]–[8]. In this paper, an embedding algorithm of multiresolution watermarking is proposed. Multiresolution signal processing is an effective method for analyzing the information content of signals, in which the images are successively approximated starting from a coarse version to a finer resolution. Since the uneven distribution of image energy, we decompose both the image and the watermark into hierarchical structures. The host gray-level image is decomposed by discrete wavelet transform. The binary watermark is decomposed by resolution reduction to obtain a pyramid of differential layers. Since the human visual system (HVS) inherently performs multiresolution structure [9], in order to embed the watermark imperceptible, each differential layer of the watermark is embedded into the corresponding decomposed layer of the host image. Then, in case of possible attacks, the coarser approximation of the watermark is hoped to still be preserved in the coarser version of the remaining image.

In most previous work, the watermark is considered a symbol or ID number which comprises a sequence of bits, and can only

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C.-T. Hsu is with the Communication and Multimedia Laboratory, Department of Computer Science and Information Engineering, National Taiwan University, Taipei, Taiwan (e-mail: candy@cmlab.csie.ntu.edu.tw).

J.-L. Wu is with the Department of Computer Science and Information Engineering, National Taiwan University, Taipei, 106, Taiwan (e-mail: wjl@cmlab.csie.ntu.edu.tw).

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be "detected" by employing the "detecting theory." The original image is subtracted from the image in question, and the similarity between the difference and specific watermark is obtained. Therefore, the similarity is compared with a predefined threshold to determine whether the image in question contains the specific watermark. In our work, the watermark is a visually recognizable pattern, which is hoped to be "extracted," instead of only "detected," to characterize the owner. Both the extracted pattern and the similarity measurement would be provided to the user to determine whether the image in question is watermarked.

This paper is organized as follows. Multiresolution representations for both the watermarks and the host images are addressed briefly in Section II. The proposed watermark embedding approach is described in Section III. Section IV describes the watermark extraction procedure. In Section V, two issues will be addressed. The experimental results are shown in Section VI. Finally, Section VII concludes the paper.

II. Multiresolution Representation

In most natural images, the energy is concentrated on the lower frequency range. In order to invisibly embed the watermark, it is expected that the lowest frequency components are left unmodified. On the other hand, in order to survive lossy data compression, the important information of the watermark should not be embedded into the higher frequency components.

The hierarchical structure of multiresolution representation provides a useful analysis mechanism for images. According to the characteristics of the HVS, both the host images and the watermarks are decomposed successively (with different mechanisms) into a hierarchical structure. Since the information hidden in the higher frequency components might be discarded after the quantization operation of lossy compression, the lower resolution watermarks should be embedded into the lower frequency components of the image, while the higher resolution differential watermarks should then be embedded into higher frequency components of the image. Notice that the components in the lowest frequency band of the image are left unmodified. Therefore, in case of compression or quality degradation, the low-resolution rendition of the watermarks will be preserved within the lower resolution components of the image.

A. Pyramid Structure of Binary Watermark

In our work, the watermark is treated as a visually recognizable binary pattern which could be a hand-written signature, specific patterns, or a seal with someone's name. To decompose such binary data with several differential layers, we take advantage of the resolution-reduction (RR) function of the joint binary image experts group (JBIG) compression standard [10]. Intuitively, subsampling a given image by a factor of two in each dimension is a simple reduction approach. However, for bilevel images containing text and line drawings, subsampling is poor because it frequently deletes thin lines [10]. JBIG suggests a resolution reduction method, as shown in Fig. 1, and this carefully designed method is used during our pyramid generating procedures of the watermarks.

After the resolution reduction, the low-resolution part is subtracted from the original one to obtain the differential layer, which is quite similar to the representation of Laplacian pyramid [11], except that module-2 addition and subtraction operations are adopted. Notice that there is no loss of the binary watermark under such a reducing and reconstructing process.

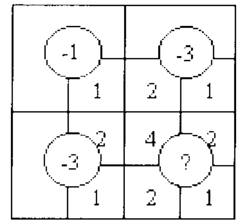


Fig. 1. Pixel weightings of resolution reduction, where low-resolution pixels are shown as circles and the corresponding high-resolution pixels are shown as squares. A target pixel is decided using not only the four corresponding high-resolution pixels, but also the periphery pixels and the already committed low-resolution pixels. The pixel "?" is decided to be 1 if the weighting result is greater than 4.5.

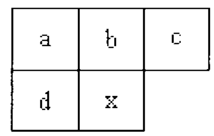


Fig. 2. The residual mask of adjacent pixels, where 'x' stands for the current pixel.

B. Wavelet Decomposition of the Host Image

The wavelet transform is used to hierarchically decompose the host image into a series of successively lower resolution reference images and their associated detail images. At each level, the low-resolution image and the detail images contain the information needed to reconstruct the reference image at the next higher resolution level.

III. Multiresolution Watermark Embedding

Assume that host image is a gray-level image, and the digital watermark is a binary pattern where the marked pixels are valued as 1's, and the others as 0's. The resolution of a watermark image is assumed to be half of that of the host image.

Discrete Wavelet Transform of the Host Image: The input image is transformed by the discrete wavelet transform (DWT) [12] to obtain a multiresolution representation.

Generating the Pyramid Structure of the Watermark: Decompose the binary watermark into a series of successively lower resolution differential layers.

Pixel-Based Pseudo Permutation of the Watermark: A pseudo-random permutation is performed first in order to disperse the spatial relationship of the binary pattern. Therefore, it would be hard for a pirate to detect or remove the watermark by just cutting some part of the image, in case the shape or the major location of the watermark is guessed. Furthermore, the noise-like watermark is statistically undetectable than a structured pattern.

A fast 2-D pseudorandom number traversing method is used to perform the permutation. First, number each pixel of the binary watermark in increasing order, starting at zero. Then, produce these numbers in random order, for example, a "linear feedback shift register" could be used to generate all numbers in a fairly random manner. Finally, generate the new coordinate pairs by mapping the random number into a 2-D sequence, and then permute the content of the original pixel into that of new coordinate pairs.

Block-Based Image-Dependent Permutation of the Watermark: In order to improve the perceptually invisibility, the characteristics of

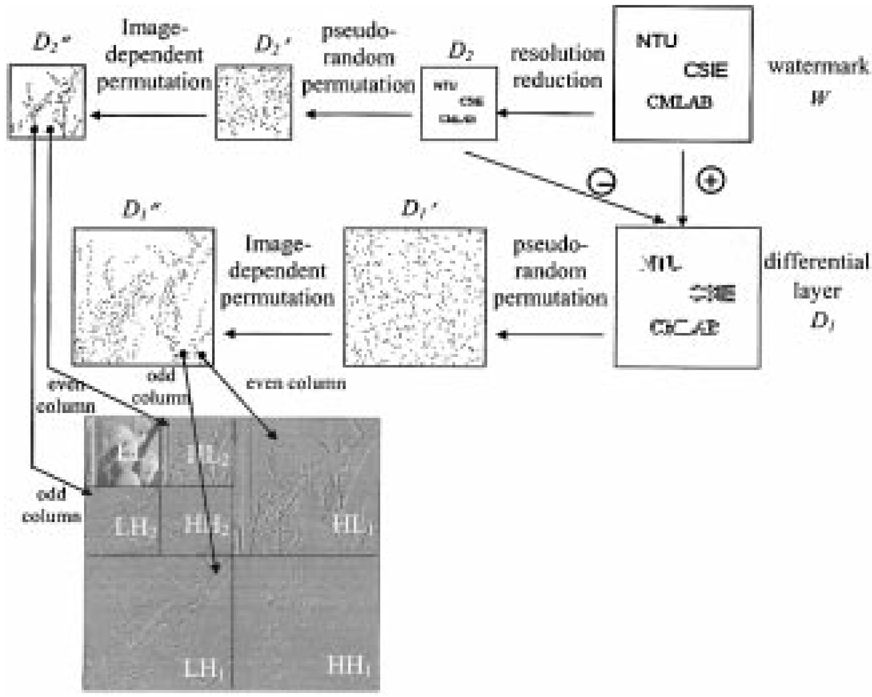


Fig. 3. Watermark embedding steps. The watermark W is decomposed into D_1 and D_2, and the host image is decomposed as $\{LL_2, HL_k, LH_k$ and $HH_k,\ k = 1, 2\}$. After the pseudorandom and image-dependent permutations, embed the D_1'' and D_2'' into the corresponding layers of the decomposed image by reversing the residual polarities.

the host image should be considered, e.g. the modifications of regions with higher frequencies are less perceptible. Such image-dependent properties can be used to shuffle the pseudorandom permuted watermark to fit the sensitivity of human eyes.

For example, if the variances of the host image are used as a measure of perceptually invisibility. First, after the decomposition and pseudorandom permutation of the host image and the binary watermark, both are divided into blocks (note that the number of blocks is hopefully the same). Then, the variance of each image block is computed and sorted and the amount of information (i.e. the number of marked pixels) is counted and sorted. Finally, shuffle each watermark block into new position according the corresponding sorting order of the image block.

Modification of DWT Coefficients: In our multiresolution embedding, the differential layers of the watermark are embedded into the detail images of the host image at the same resolution. There are various embedding techniques to achieve this work. However, in our experiments, due to the orthogonalty of the wavelet transform, modification between detail images of the same resolution could result in obvious visual artifacts. Therefore, in the proposed method, the watermarks are embedded into the "neighboring relationship" within the detail images.

A residual mask is used to perform the embedding procedure. That is, the watermark is not embedded as an additive noise. Instead, the watermarks are embedded into the "neighboring relationship" within the transformed images. First, compute the residual polarity between the neighboring pixels according to the specified residual mask. For each marked pixel of the permuted watermark, modify the relevant pixels of the DWT coefficients of the host image by either addition or subtraction, such that the residual polarity of the modified sequence becomes the reverse of the original polarity (i.e., the NOT operation for binary sequence). For example, in Fig. 2, if $a = b = c = 0,\ d = -1,\ x = 1$, then the residual value is the difference between the current and the previous pixels. That is, the residual polarity is set as "1" if the coefficient of the current pixel is larger than that of the former one, and is set as "0" otherwise. During the extracting procedure, perform the exclusive-or (XOR) operation upon the polarities from both the original and the modified sequences to obtain the extracted result.

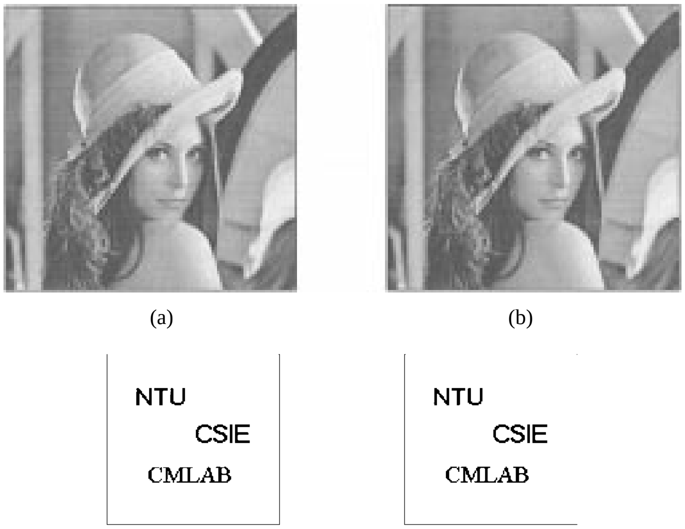
The quantity of modification is used as a parameter to control the invisibility and also the robustness. Note that this kind of modification is noninvertible without the knowledge of the host image. Fig. 3 shows an example of watermark embedding steps, where the decomposition level is set as 2.

Inverse Wavelet Transform: Finally, inverse DWT of the associated result to obtained the embedded image.

IV. Watermark Extracting Procedures

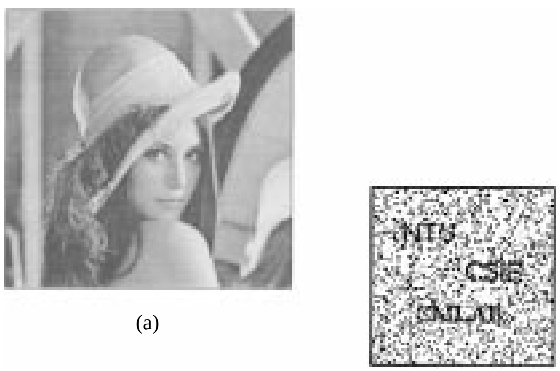
The extraction of the watermark requires both the original and the watermarked images. They are needed not only in obtaining the permutation mapping specified in image-dependent permutation, but also in computing the correlation with the extracted result, as a watermark verification process. The extraction steps are as follows:

1) *discrete wavelet transformation:* both the original image and the watermarked image are DWT transformed;
2) *generation of the residual results:* make use of the residual masks applied during the embedding step, generate the residual results for the detail images;
3) *extract the permuted differential watermarks:* for each level, perform the XOR operation on the residual results to obtain the permuted binary data;
4) *reverse the permutations:* the image-dependent permutation mapping can be obtained from the original detailed image and the differential watermark; then, reverse the image-dependent permutation by the image-dependent permutation mapping, and



(a) (b) (c) (d)

Fig. 4. (a) The test image "Lena" of size 256×256, (b) the watermarked image ($\mathrm{PSNR} = 44.18$ dB), (c) the watermark, and (d) the extracted watermark ($\mathrm{NC} = 1$).



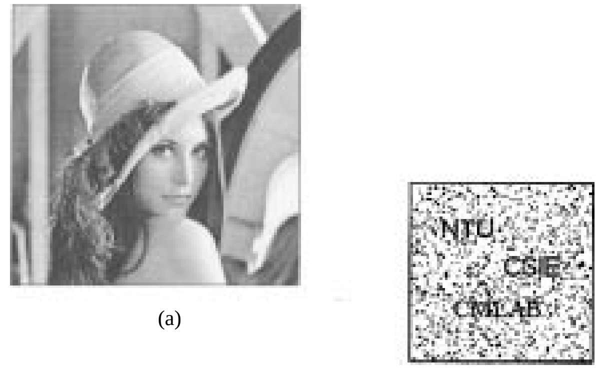
(a) (b)

Fig. 5. (a) Blurred version of Fig. 4(b), and (b) is the extracted watermark with $\mathrm{NC} = 0.74$.

follow with the pseudorandom permutation according to the predefined pseudorandom order;

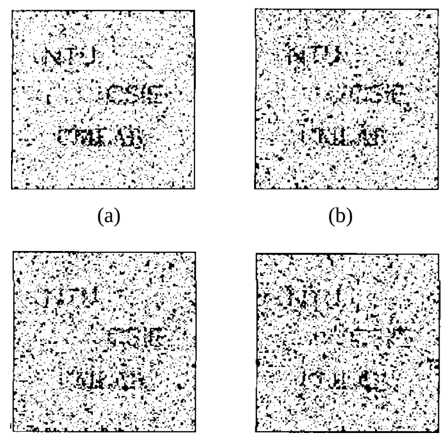
5) *reconstruct the watermark:* having a pyramid of differential watermarks, successively reconstruct the higher-resolution layers to obtain the extracted watermarks;
6) *similarity measurement:* after extracting the watermark, the user can compare the results with the referenced watermark subjectively. However, since the subjective measurement will be affected by the factors of image size, expertise of the observers, experimental conditions, etc., a quantitative measurement is required to provide objective judgment of the extracting fidelity. Therefore, a similarity measurement of the extracted watermark $\hat{W}(i,j)$ and the referenced watermark $W(i,j)$ can be defined as

$$\mathrm{NC} = \sum_{i=0}^{(N/2)-1} \sum_{j=0}^{(N/2)-1} W(i,j)\hat{W}(i,j) \Bigg/ \sum_{i=0}^{(N/2)-1} \sum_{j=0}^{(N/2)-1} [W(i,j)]^2$$



(a) (b)

Fig. 6. (a) Contrast-enhanced version of the watermarked image (Fig. 4(b)), and (b) is the extracted watermark with $\mathrm{NC} = 0.925$.



(a) (b) (c) (d)

Fig. 7. The extracted watermarks of JPEG compressed version of the watermarked image (Fig. 4(b)), where (a) with compression ratio 3.48 and $\mathrm{NC} = 0.777$, (b) with compression ratio 5.26 and $\mathrm{NC} = 0.6816$, (c) with compression ratio 6.68 and $\mathrm{NC} = 0.605$, and (d) with compression ratio 8.04 and $\mathrm{NC} = 0.561$.

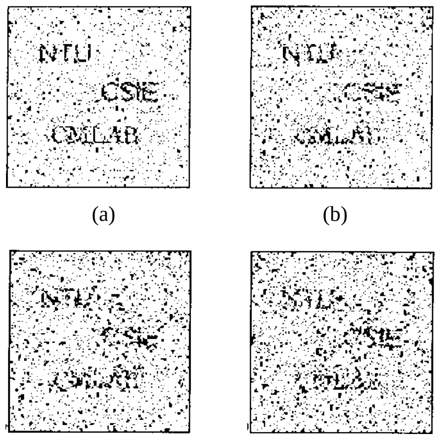
which is the cross correlation normalized by the reference watermark energy to give unity as the peak correlation.

V. Discussion

A multiresolution-based watermarking technique for digital images is proposed in this paper. There are some issues worthy of giving further exploration and discussion.

User Key: In order to provide different embedding alternatives, the mechanism of "user key" is included in our algorithm. A "user key" is considered an additional feature that can be implemented to serve various embedding processes by using the same embedding technology. For example, it could be used to designate different "seeds" of the pseudorandom number traversing method, different decomposition levels, different patterns of the residual mask, and/or the specific bands (such as LH, HL or HH) that will be used to embed the watermark.

Evaluation of Wavelet Filters: Choice of wavelet filters is also a critical issue that affects the quality of the watermarked image and the robustness to compression attacks. A lot of biorthogonal wavelet filters have been evaluated for their compression performance based only on the reference signal at the lowest resolution level [13]. For



(a) (b) (c) (d)

Fig. 8. The extracted watermarks of JPEG compressed image "Lena" with size 512×512, where (a) with compression ratio 10.82, (b) with compression ratio 14.76, (c) with compression ratio 16.08, and (d) with compression ratio 20.51.

those filters having better compression performance given in [13], the information is largely preserved in the lowest resolution reference image, i.e., most of the energy about the original image is packed into the reference image, and therefore the information in the detail images can be discarded without any salient quality degradation. Using such filters in our method, all of the watermarking information hidden in the images will be soon and easily discarded by compression operations.

Therefore, from the watermarking point of view, the evaluation of filters will be quite different than those based purely on compression performance. Conversely, watermarking techniques have to make use of the redundancy within the detail images and also keep the image quality. The evaluation of suitability of wavelet filters for invisible watermarking is currently being explored, and the wavelet filters applied to our following experiments are the Daubechies tap-6 filters [12].

VI. Experimental Results

The image "Lena" is used as our test image. Fig. 4 shows the original host image, the binary watermark, the watermarked image, and the extracted result.

Image Processing Operation: Fig. 5 shows a blurred version of the watermarked image, and the extracted result still with high NC value (0.74). Fig. 6 shows a contrast-enhanced version of the watermarked image and the corresponding NC value of 0.925.

JPEG Lossy Compression: Fig. 7 shows the extracted watermarks from JPEG compressed version of Fig. 4(b), with compression ratio from 3.48, 5.26, 6.68 to 8.04, and the corresponding NC values of the extracted watermarks of 0.777, 0.6816, 0.605 and 0.561, respectively. Fig. 8 shows the extracted watermarks from JPEG compressed version of larger image "Lena" (size 512×512), which can resist larger compression ratio than smaller images do.

VII. Conclusion

In this paper, a multiresolution watermark embedding algorithm is proposed. With the characteristics of successive approximation, as higher resolution images are obtained, the higher resolution watermark will be extracted, and when only coarse resolution of the image is available, the coarser approximation of the watermark can be extracted. Experimental results are presented to claim the robustness and correctness of the proposed watermarking process.

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