Space/Spatial-Frequency Based Image Watermarking

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Abstract - *An image watermarking procedure in the space/spatial-frequency domain is proposed. Space/spatial-frequency regions to be watermarked are selected by using the two-dimensional spectrogram. In order to provide both the imperceptibility and robustness of the procedure, a watermark is modeled according to the specific characteristics of pixels' regions. The inversion from the space/spatial-frequency domain is provided by using the concept of space-varying filtering. The correlation based watermark detection is performed in the space/spatial-frequency domain as well. The efficiency of the proposed procedure is tested in the presence of various common signal processing.*

Keywords - *Image watermarking, Space/spatial-frequency representations, Space-varying filtering*

1. INTRODUCTION

In the last decade digital watermarking has been intensively developed as a tool for data copyright protection. In general, watermark should be imperceptible within the host data and robust to intentional and unintentional attacks. The existing image watermarking algorithms are performed either in spatial or spectral domain. In the spatial domain, the watermarking regions are selected according to the image textures and luminance changes. However, within this domain, it is very difficult to provide good imperceptibility and robustness, simultaneously. Transform domain watermarking techniques are more robust comparing to the spatial domain techniques. They are mainly based on watermark embedding in the middle or low to middle frequency regions of the DFT, DCT or Wavelet transform. Watermark added to these frequency components will be spread over all the pixels from a considered region. Thus, in order to make the watermark imperceptible, some additional masking procedure is necessary. In order to take the advantage of both domains, the joint space/spatial-frequency domain can be considered for watermarking. An interesting approach based on the two-dimensional Radon-Wigner distribution has been given in [1]. Also, the use of Wigner distribution in image watermarking has been reported in [2] and [3]. However, it is applied on image columns or rows, and does not contain the information about frequency content for a single pixel. Therefore, the main idea of this paper is to provide a tool for the local frequency content estimation of each individual image pixel, which will be used for watermarking. Also, the space/spatial-frequency domain provides the information about local frequency spreading in the region around considered pixel. Thus, a method for watermark modeling corresponding to the local frequency content of image pixels is proposed. In order to satisfy imperceptibility and robustness requirements, the watermark energy is adapted to the energy of considered pixels' region. The two dimensional space/spatial-frequency representation is obtained by using the two-dimensional spectrogram. In order to provide the inverse mapping from the space/spatial-frequency domain, the space-varying filtering procedure is employed. The similar concept based on the time-varying filtering of one-dimensional signals has been used in [4]. The watermark detection has also been provided, as well as the measure of detection efficiency. The proposed procedure has been tested on various images and under common signal processing (attacks).

2. THEORETICAL BACKGROUND

Space/spatial domain and frequency domain, separately, can be used for stationary signals analysis. However, in the case of highly non-stationary signals, such as images, the more efficient analyses are provided in the joint space/spatial-frequency domain. Therefore, in this section, we provide the basics of space/spatial-frequency representation and the concept of space-varying filtering that will be used in the proposed image watermarking procedure.

2.1. Space/spatial-frequency representation

The simplest and commonly used space/spatial-frequency representation is spectrogram. It is defined as a square module of the short-time Fourier transform. The two-dimensional short-time Fourier transform can be written as:

$$STFT(n_1,n_2,k_1,k_2)=\sum_{i_1=-(N/2)+1}^{N/2}\sum_{i_2=-(N/2)+1}^{N/2} s(n_1+i_1,n_2+i_2)\times \times w(i_1,i_2)e^{-j(2\pi/N)(k_1 i_1+k_2 i_2)} \quad (1)$$

where (n_1,n_2) and (k_1,k_2) are the discrete space and frequency variables, while N is the length of signal. Thus, in the case of 2-D signals such as images, the space/spatial frequency representation is a 4-D function, i.e. each pixel is represented by the 2-D function that contains the information about its local frequency content.

2.2. Space-varying filtering

The concept of time-varying filtering has been developed for noisy signals filtering. In analogy with one-dimensional case, space-varying filtering for 2-D signal $s(\vec{r})=s(x,y)$ has been defined as [5]:

$$Hs(\vec{r})=\int_{-\infty}^{\infty} h(\vec{r}+\frac{\vec{v}}{2},\vec{r}-\frac{\vec{v}}{2})w(\vec{v})s(\vec{r}+\vec{v})d\vec{v}\,, \quad (2)$$

where $w(\vec{v})$ represents lag window, while $h(\vec{r},\vec{v})$ is the impulse response of the space-varying filter.

Space-varying transfer function, i.e. support function, has been defined as Weyl symbol mapping of the impulse response into the space/spatial-frequency domain:

$$L_H(\vec{r},\vec{\omega})=\int_{-\infty}^{\infty} h(\vec{r}+\frac{\vec{v}}{2},\vec{r}-\frac{\vec{v}}{2})e^{-j\vec{\omega}\vec{v}}d\vec{v}, \quad (3)$$

where $\vec{r}$ and $\vec{w}$ are space and frequency variables, respectively.

According to (2), (3) and by using the Parseval's theorem, follows:

$$Hs(\vec{r})=\frac{1}{2\pi}\int_{-\infty}^{\infty} L_H(\vec{r},\vec{\omega})STFT_s(\vec{r},\vec{\omega})d\vec{\omega}. \quad (4)$$

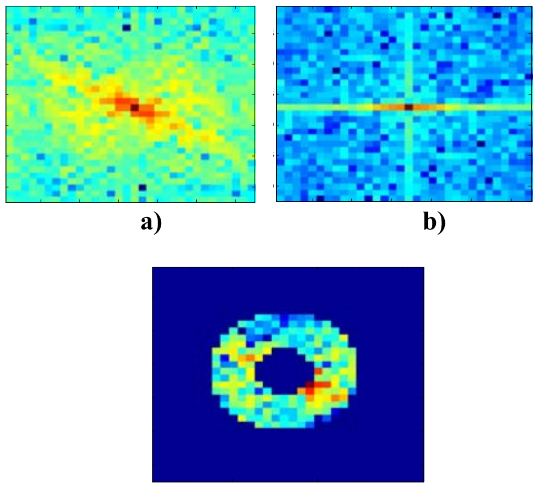
Thus, $Hs(\vec{r})$ represents the output of the space-varying filter. In the proposed watermarking procedure space-varying filtering will be used to retrieve watermarked signal from the space/spatial-frequency domain. Also, the support function of a space-varying filter will be used to adapt watermark energy to the local energy of original image.

3. WATERMARKING PROCEDURE

The procedure for image watermarking based on the space/spatial-frequency representation is proposed in this Section. This method includes watermark modeling, watermark embedding procedure and correlation based watermark detection within the space/spatial-frequency domain.

3.1. Watermark modeling

Let us consider the space/spatial-frequency representation of a single pixel. According to (1), the STFT is calculated using the space window that contains N×N pixels around the considered one. Thus, the spectrogram will contain information about stationarity of the windowed region. The image regions that contain edges and high luminance changes can be considered as non-stationary regions. The spectrogram of these regions will have significant components on almost all frequencies (Fig. 1.a). On the other side, stationary image regions are of slow varying luminance and do not contain edges. The components of such regions will be concentrated in the low frequency regions (Fig 1.b). Thus, the idea is to create watermark that will correspond to the local frequency content of image pixels.



a) b)

c)

Fig. 1. a) Spectrogram of an image pixel, b) middle frequency region D

The low frequency components (around (0,0) frequency) are of high energy. The watermark modeled according to these components will be also of high energy which will provide its robustness, but it may cause perceptual degradation. On the other side, watermark modeled according to the high frequency components will not be robust enough. Thus, in order to fulfill both the imperceptibility and robustness, the middle frequency region $D=\{(\omega_1,\omega_2):p^2<\omega_1^2+\omega_2^2<q^2\}$ is considered for watermarking, Fig 1.c) (p and q are lower and upper radius of middle frequency region, respectively). The support function of the considered region D can be defined as:

$$L_M(\omega_1,\omega_2)=\begin{cases}1 & \text{if} \quad (\omega_1,\omega_2)\in D\\ 0 & \text{otherwise.}\end{cases} \tag{5}$$

This function is used to model frequency characteristics of watermark. In order to additionally improve the robustness, only the strongest middle frequency components are selected by introducing the threshold value: $T=10^{\lambda\cdot\log_{10}(\max(SPEC_D(\omega_1,\omega_2)))}$. The notation $\max(SPEC_D(\omega_1,\omega_2))$ represents the maximal value of the spectrogram within the region D, while λ is a scaling parameter with values between 0 and 1. The higher λ means that stronger components are considered, and vise versa. By applying the threshold T the modified support function will be obtained as:

$$L_{MT}(\omega_1,\omega_2)=\begin{cases}1, & \text{for} \quad (\omega_1,\omega_2)\in D \ \text{and} \ SPEC(\omega_1,\omega_2)>T\\ 0, & \text{for} \quad (\omega_1,\omega_2)\notin D \ \text{or} \ SPEC(\omega_1,\omega_2)\leq T.\end{cases} \tag{6}$$

Further, the function L_{MT} is combined with the short-time Fourier transform of a starting 2-D pseudo-random sequence, in order to obtain the watermark with specific space/spatial frequency characteristics:

$$\begin{aligned}&STFTwat(n_1,n_2,\omega_1,\omega_2)=L_{MT}(\omega_1,\omega_2)\times\\ &\times STFTp(n_1,n_2,\omega_1,\omega_2)\end{aligned} \tag{7}$$

where $STFTp$ is the short-time Fourier transform of a pseudo-random sequence, while $STFTwat$ is the resulting short-time Fourier transform of watermark.

3.2. Watermark embedding procedure

Watermark embedding procedure is performed in the space/spatial frequency domain, as follows:

$$\begin{aligned}&STFT_{Iw}(n_1,n_2,\omega_1,\omega_2)=STFT_I(n_1,n_2,\omega_1,\omega_2)+\\ &+STFTwat(n_1,n_2,\omega_1,\omega_2)\end{aligned} \tag{8}$$

where $STFT_I$ is the short-time Fourier transform of original image, while $STFT_{Iw}$ is short-time Fourier transform of watermarked image.

In order to retrieve the signal from its space/spatial-frequency representation the concept of space-varying filtering is applied. Input of the space-varying filter is $STFT_{Iw}$, while the support function is defined as:

$$L(\omega_1,\omega_2)=\begin{cases}1 & \text{if} \quad SPEC(\omega_1,\omega_2)>0\\ 0 & \text{otherwise.}\end{cases} \tag{9}$$

According to (4), the watermarked image pixel on the position (n_1,n_2) is obtained as:

$$Iw(n_1,n_2)=\frac{1}{2\pi}\sum_{\omega_1}\sum_{\omega_2}STFT_{Iw}(n_1,n_2,\omega_1,\omega_2)L(\omega_1,\omega_2). \tag{10}$$

3.3. Watermark detection procedure

Watermark detection is performed by using the standard correlation detector in the space/spatial-frequency domain:

$$D=\sum_{\omega_1}\sum_{\omega_2}STFT_{Iw}(n_1,n_2,\omega_1,\omega_2)\cdot STFTwat(n_1,n_2,\omega_1,\omega_2). \tag{11}$$

The detection performance is tested by using the following measure of detection quality:

$$R=\frac{\overline{D}_{w_r}-\overline{D}_{w_w}}{\sqrt{\sigma^2{}_{w_r}+\sigma^2{}_{w_w}}}, \tag{12}$$

where $\overline{D}$ and σ^2 represent the mean value and the standard deviation of the detector responses, while notations w_r and w_w indicate the right and wrong keys (trials), respectively. The probability of error P_{err} can be easily calculated by using measure R, as follows:

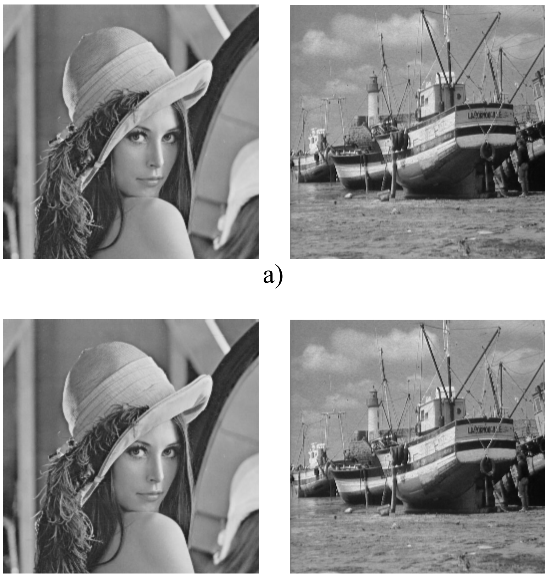
$$P_{err}=\frac{1}{2}erfc\left(\frac{R}{\sqrt{2}}\right), \tag{13}$$

where the normal distribution of detector's responses is assumed. Probability of detection is obtained as $P_d=1-P_{err}$. By increasing the value of measure R the probability of detection error decreases. For example, $P_{err}(R=3)=0.0013$, $P_{err}(R=4)=3\cdot10^{-5}$, while $P_{err}(R=5)=2.6.10^{-7}$.

4. EXAMPLE

In order to show the efficiency of the proposed procedure, the following example is considered. Two-dimensional STFT is calculated by using non-overlapping rectangular space window of size 8×8. The middle frequency region $D=\{(\omega_1,\omega_2):5<\omega_1^2+\omega_2^2<20\}$ is selected for watermarking. The threshold T is obtained by using parameter λ=0.5. The support function L_{MT}, used for watermark modeling, is determined according to (6).

Original and watermarked images Lena and Boat are show in Fig. 2. The difference between original and watermarked image is negligible. The peak signal to noise ratio (PSNR) is around 45 dB (average value for 100 trials).



a)

b)

Fig. 2. a) Original images, b) Watermarked images

The watermarking procedure has been done for 100 different right keys (watermarks). For each of the right keys, R is calculated for 100 wrong trials. The values of measure R for various images and various considered attacks are shown in Table 1.

Table 1. Measures of Detection Performance

Image	**Proposed procedure**		**Standard procedure**	
Lena	**R**	**Perr**	**R**	**Perr**
No attack	7.1	$5.3\cdot10^{-13}$	3.9	$4.8\cdot10^{-5}$
JPEG 80	4.8	$7.3\cdot10^{-7}$	3.2	$6.8\cdot10^{-4}$
JPEG 50	3.4	$3\cdot10^{-4}$	2.4	$8.2\cdot10^{-3}$
Median 3x3	3.4	$3\cdot10^{-4}$	2	$2.3\cdot10^{-2}$
Gaussian noise	6.4	$6.8\cdot10^{-11}$	3.3	$4.8\cdot10^{-4}$
Impulse noise	6.5	$3.5\cdot10^{-11}$	3.4	$3.3\cdot10^{-4}$
Pepper	**R**	**Perr**	**R**	**Perr**
No attack	6.7	$9\cdot10^{-12}$	3.2	$6.87\cdot10^{-4}$
JPEG 80	4.6	$2\cdot10^{-6}$	2.6	$4.7\cdot10^{-3}$
JPEG 50	3.4	$3\cdot10^{-4}$	2	$2.3\cdot10^{-2}$
Median 3x3	3.1	$9.4\cdot10^{-4}$	1.3	$9.7\cdot10^{-2}$
Gaussian noise	6.1	$4.7\cdot10^{-10}$	2.6	$4.7\cdot10^{-3}$
Impulse noise	6	$8.8\cdot10^{-10}$	2.7	$3.5\cdot10^{-3}$
Baboon	**R**	**Perr**	**R**	**Perr**
No attack	7.2	$2.5\cdot10^{-13}$	3.6	$1.6\cdot10^{-4}$
JPEG 80	5.5	$1.7\cdot10^{-8}$	3	$1.3\cdot10^{-3}$
JPEG 50	4.5	$3.2\cdot10^{-6}$	2.2	$1.4\cdot10^{-2}$
Median 3x3	3.3	$4.6\cdot10^{-4}$	1.8	$3.6\cdot10^{-2}$
Gaussian noise	6.8	$4.5\cdot10^{-12}$	3.1	$9.6\cdot10^{-4}$
Impulse noise	6.7	$9\cdot10^{-12}$	3.2	$6.8\cdot10^{-4}$
Boat	**R**	**Perr**	**R**	**Perr**
No attack	7.7	$5.6\cdot10^{-15}$	3.4	$3.3\cdot10^{-4}$
JPEG 80	5.8	$3\cdot10^{-9}$	2.6	$4.7\cdot10^{-3}$
JPEG 50	4.4	$5\cdot10^{-6}$	1.8	$3.6\cdot10^{-2}$
Median 3x3	3.2	$6.6\cdot10^{-4}$	1.4	$8\cdot10^{-2}$
Gaussian noise	6.5	$3.5\cdot10^{-11}$	2.9	$1.9\cdot10^{-3}$
Impulse noise	5.9	$1.6\cdot10^{-9}$	3	$1.3\cdot10^{-3}$

The proposed approach provides very low probabilities of error for most of the considered attacks.

Additionally, in order to make a comparison with the proposed method, a non-modeled watermark created as Gaussian pseudo-random sequence has been embedded in the image pixels by using the standard additive procedure with the same PSNR (45 dB). It is shown (Table 1) that in this case the obtained measures of detection efficiency are significantly lower i.e. the probability of error is increased compared to the results obtained for the proposed procedure.

5. CONCLUSION

A new approach to image watermarking in the space/spatial-frequency domain is proposed. In order to provide imperceptibility and robustness, the watermark is modeled and adapted to the local frequency content of the considered image pixels. Inversion from the space/spatial-frequency domain is done by using the concept of space-varying filtering. The watermark detection procedure in the space/spatial-frequency domain is provided. Robustness of the proposed procedure is tested under various attacks. Therefore, the procedure ensures reliable watermark detection with low probability of detection error for most of the considered cases.

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