A Robust and Imperceptible Digital Image Watermarking Scheme in Transform Domain Using Particle Swarm Optimization

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Abstract— Watermarking technique has been proposed as the most effective method for multimedia data security protection application. It is a process which inserts secret data (or watermark) into the main document without causing significant quality loss. Copyright protection applications require robust watermarking scheme which can resist both accidental and intentional attacks. In this paper, a robust and imperceptible image watermarking scheme using discrete wavelet transform (DWT), singular value decomposition (SVD) and particle swarm optimization (PSO) techniques is proposed. Best regions for binary watermark insertion have been selected using Canny edge detection technique. Optimized multiple scaling factors (MSF) are used to modify the coefficients during the embedding process. Different standard grayscale images have been used as test images, and the obtained experimental results show that the proposed watermarking scheme is able to achieve the highest robustness and imperceptibility level which are the most desired watermarking properties for many applications.

Keywords—Digital image watermarking, Imperceptibility, Robustness, Particle swarm optimization, DWT, SVD

I. INTRODUCTION

Nowadays, the rapid advancement of digital technology and availability of fast speed internet made the task of copying, modifying, sharing and storing digital data easier. This advantage has also created a means for pirates or attackers to illegally copy, modify or redistribute digital properties of others without the consent of the legit owners. This issue leads to the need for strong copyright and copy protection techniques. Cryptography has been used as a method to deliver digital content to a legit customer in a secure way. A person who has decryption key can only access the content. However, the drawback of cryptography is, it loses the security if once the content is decrypted and shared by an untrustworthy customer. The recently emerged technique known as digital watermarking has been proposed as the best method to keep the security of multimedia content in a stronger way [1, 2]. Watermarking is a technique that inserts copyright or other information called watermark into a host content (image, audio or video), and the embedded information can be extracted later to obtain information related to ownership. The field of digital watermarking has gained popularity as a research topic since
1993 when A. Z. Tirkel et al. [3] presented methods to hide information in images. In this work, a grayscale image is used as host or cover signal. Digital watermarking can be also used for other applications, namely, copy protection, content authentication, tamper detection and broadcast monitoring [4].

A watermarking scheme consists of two major processes, namely watermark embedding and extraction/detection. In Fig. 1 the block diagram of the generic watermarking scheme is shown. A watermark embedding process $E_M(.)$ takes an original image ($G$), watermark ($W$) and key ($K_E$) as input and perform embedding process to give a watermarked image ($G_W$).

$$G_W = E_M(G, W, K_E)$$ (1)

The watermarked image may be transmitted through an insecure channel where it can be attacked by intruders or pirates. The extraction process extracts the inserted watermark from the attacked watermarked image and this extraction procedure is defined as follows.

$$W_F = E_X(G_W^*, K_E, [W],[G])$$ (2)

Where, $E_M(.)$ and $G_W^*$ represent extraction process and an attacked Watermarked image respectively. The enclosed braces around $W$ and $G$ are used to denote optional input for watermark extraction. So, based on the input data required for watermark detection, a watermarking scheme can be categorized into non-blind, blind and semi-blind [5]. A watermarking scheme which requires an original image or copy of inserted watermark for extraction/detection process is known as non-blind watermarking scheme. Whereas, a watermarking scheme is called blind if the extraction process does not need original host image and watermark as an input signal. This type of scheme extracts/detects a watermark only using a secret key.

![Fig. 1. Block diagram of a generic watermarking scheme.](image)

For most watermarking applications that do not have access to original images, blind watermarking schemes are highly preferable.

Watermarking schemes can be also classified into fragile, semi-fragile and robust depending upon the ability of embedded information to resist different attacks. A watermarking scheme is called fragile if the inserted information is easily altered or destroyed due to slight change takes place in the watermarked image. However, for robust watermarking, the inserted watermark is able to withstand different signal processing attacks which are performed on the watermarked image. Furthermore, watermarking schemes can be grouped into spatial, transform, or hybrid based on the domain of the technique employed to insert a watermark. Spatial domain watermarking technique embeds a watermark directly by altering the pixel value of the cover image. This type of watermarking technique is computationally simple and easy to implement. On the other hand, transform domain watermarking technique inserts a watermark into host image by modifying the transformed coefficients. Generally, this watermarking technique enables more information hiding capacity and provides more robust watermarked image compared to a spatial domain techniques. Discrete cosine transform (DCT), Discrete Fourier Transform (DFT), Discrete Wavelet Transform (DWT) and Singular Value Decomposition (SVD) are the most popular transform methods which have been used most frequently in transform domain watermarking scheme [6-8].

In the watermarking field, robustness and imperceptibility are the two most sought properties. In fact, both of them have an inverse relationship. The term imperceptibility refers to the degree of similarity between original and watermarked image. In fact the watermark embedding process causes visual quality degradation on the original image due to the added signal. However, the process should maintain the quality of watermarked image at an acceptable level. So, the main challenge in designing a watermarking scheme for copyright
The rest of this paper is organized as follows: In section II, the basics of DWT, SVD, and PSO are presented. Section III presents the proposed watermark embedding and extracting procedures in detail. Experimental results are given in section IV. Finally, the conclusion is stated in section V.

II. FUNDAMENTALS OF DWT, SVD AND PSO

A. DWT based image multi-resolution decomposing

Discrete Wavelet transform (DWT) is the most powerful tool for signal multi-resolution analysis. The transform is based on the small waves know as wavelets which have varying frequency and limited duration [13]. The Haar wavelet is the simplest possible wavelet. DWT decomposes an image into four different frequency sub-bands known as an approximation (LL), horizontal (HL), vertical (LH) and diagonal (HH) sub-bands. It has excellent space frequency localization property, and it can best model human visual system (HVS). The significant information of an original image is preserved in LL sub-band. A two-dimensional discrete wavelet transform can be viewed as a 1-D wavelet system that performs transforms along the rows and then a 1-D wavelet transforms along the columns. A 2-D scaling \( \psi(x, y) \) and three 2-D wavelets, \( \psi^H(x, y) \), \( \psi^V(x,y) \) and \( \psi^D(x,y) \) are required to measure intensity changes in the image along horizontal, vertical and diagonal direction. Fig. 2 shows 1-level DWT.

B. Singular value decomposition

Singular value decomposition is a linear algebra technique which uses to factorize a given matrix into three unique matrices. Because of its advantages, SVD has been used widely for image watermarking application [14]. The SVD of image \( G \) of size \( M \times N \) gives three other matrices known as \( U \), \( S \), and \( V \) such that

\[
G = U S V^T
\]  

(3)

Where, \( G \in \mathbb{R}^{M \times N} \), \( U \in \mathbb{R}^{M \times M} \), \( S \in \mathbb{R}^{M \times N} \) and \( V \in \mathbb{R}^{N \times N} \). \( U \) and \( V \) are called left and right singular matrices. \( S \) is a nonnegative diagonal matrix containing the square root of the eigenvalues of either \( U \) or \( V \). The elements of \( S \) matrix are arranged in descending order diagonally i.e., \( s_1 \geq s_2 \geq \cdots \geq s_{MN} \). In this paper, we have used block based SVD to embed a binary watermark by modifying singular values using multiple scaling factors. The following are a list of benefits that we can get when we use SVD for image watermarking.

- The visual quality of the image is not affected significantly due to a slight change of singular values.
- Singular values have good stability and their values are rotationally invariant.
SVD can pack a large energy signal within few coefficients.

C. Particle swarm optimization

The quantity of signal embedded into host image has a direct impact on the robustness and imperceptibility. In watermarking, this embedding quantity can be controlled by varying the magnitude of scaling factors. So, the problem of finding best scaling factors that can provide improved performance and maintain the balance between robustness and imperceptibility can be considered as an optimization problem. The objective of optimization is given as follows:

\[
\begin{align*}
\text{Maximize} & : R(\sigma_k) \\
\text{Maintaining} & : Q(\sigma_k) \geq Q_{th}
\end{align*}
\]  

(4)

Where, \( R(\cdot) \) and \( Q(\cdot) \) refer robustness and imperceptibility respectively. \( \sigma_k \) is the \( k \)-th scaling factor and \( Q_{th} \) is a user defining quality threshold. Putting the above objectives into consideration, the fitness function (ff) is formulated as follows.

\[
\text{ff} = \begin{cases} 
\text{PSNR}(G, G_w) + \eta \sum_{i=1}^{n} \text{NCC}(W, W_E) 
\end{cases}
\]  

(5)

Where, PSNR (.) and NCC (.) are metrics to measure imperceptibility and robustness respectively. \( G \) and \( G_w \) are original and watermarked image respectively; while \( W \) and \( W_E \) are original and extracted watermark respectively.

In this work, PSO algorithm is adopted to obtain optimized best multiple scaling factors. Particle swarm optimization technique was first developed by Eberhart and Kennedy in 1995 [15]. The first step in PSO is generating particle randomly having position \( x_i(t) \) and velocity \( v_i(t) \). At each iteration, the velocity and position of particles are computed by using the following equation.

\[
v_i(t+1) = v_i(t) + C_1 \text{rand} (p_{best} - x_i(t)) + C_2 \text{rand} (g_{best} - x_i(t))
\]

(6)

\[
x_i(t+1) = x_i(t) + v_i(t+1)
\]

(7)

Where, \( p_{best} \) and \( g_{best} \) are personal best and global best of the particles at a given iteration. \( W_i \) is inertia weight which determines the step size, \( C_1 \) and \( C_2 \) are learning factors which determine the effectiveness of local and global learning. The term ‘rand’ refers to an operation which randomly generates numbers between 0 and 1. Fig. 3 shows a flow chart for PSO based optimum scaling factor searching algorithm.

III. PROPOSED WATERMARKING ALGORITHM

The proposed watermarking scheme consists of watermark embedding and extracting algorithms. In the following subsection, the embedding and extracting procedures are discussed exhaustively.

A. Proposed watermark embedding algorithm

The proposed embedding algorithm takes a cover image (G) and a binary watermark (W) as input and performs embedding...
process to give the watermarked image \((G_w)\) as an output. The embedding process involves the following steps.

Step 1: Perform block-based canny edge detection operation on the cover image and form two sub-images \((G_1)\) and \((G_2)\) merging selected blocks.

Step 2: Apply 1-level DWT on \(G_1\) and \(G_2\).
\[
\begin{align*}
(LL_1, LH_1, HL_1, HH_1) &= DWT(G_1) \\
(LL_2, LH_2, HL_2, HH_2) &= DWT(G_2)
\end{align*}
\] (8)

Step 3: Take approximation sub-bands \((LL_1\) and \(LL_2\) and perform block-based SVD operation.
\[
(U_1, S_1, V_1) = SVD(LL_1)
\]
\[
(U_2, S_2, V_2) = SVD(LL_2)
\] (9)

Step 4: Use multiple scaling factors \((\sigma_1)\) which are obtained from PSO and insert binary watermark bits using the following rule.
\[
S_{W_{(m,n)}}(x,y) = \begin{cases} 
0 & \text{if } W(m,n) = 0 \\
1 & \text{otherwise} \\
\sigma_1 & \text{if } S_{(m,n)}(x,y) > S_{2(m,n)}(x,y) \\
S_{(m,n)}(x,y) - \sigma_2 S_{2(m,n)}(x,y) & \text{if } S_{(m,n)}(x,y) < S_{2(m,n)}(x,y)
\end{cases}
\] (10)

Where, \(x=y=1\) and \((m,n)\) represent block indices. The scaling factor \(\sigma_i\) if the magnitude of \(|S_{(m,n)}(x,y) - S_{2(m,n)}(x,y)|\) is in the interval of range \(r_i\).

Step 5: Apply inverse SVD to obtain watermarked \(LL_1\) sub-band.
\[
LL_{bw} = U_1 S_W V_1^T 
\] (11)

Step 6: perform inverse DWT using watermarked \(LL_1\) sub-band to get watermarked sub-image \(G_1\).
\[
G_{bw} = IDWT(LL_{bw}, LH_1, HL_1, HH_1) 
\] (12)

Step 7: Finally, merge the two sub-images \((G_{1w})\) and \((G_2)\) and place the blocks back to their original place using position key \(K_p\) to get watermarked image \(G_w\).

B. Proposed watermark extraction algorithm

Only watermarked image and key \(K_p\) are required for watermark extraction. The steps involved in the proposed extraction algorithm are presented as follows.

Step 1: Take possibly an attacked watermarked image \((G_w)\) and split it into two sub-images using the procedure discussed above and key \(k_p\).

Step 2: Perform DWT on sub-images
\[
(LL_{1w}, LH_{1w}, HL_{1w}, HH_{1w}) = DWT(G_{1w})
\]
\[
(LL_{2w}, LH_{2w}, HL_{2w}, HH_{2w}) = DWT(G_{2w})
\] (13)

Step 3: Factorize \(LL_{1w}\) and \(LL_{2w}\) using SVD
\[
(U_{1w}, S_{1w}, V_{1w}) = SVD(LL_{1w})
\]
\[
(U_{2w}, S_{2w}, V_{2w}) = SVD(LL_{2w})
\] (14)

Step 4: Finally, extract the watermark using the following rule.
\[
W_E(m,n) = \begin{cases} 
1 & \text{if } S_{1w(m,n)}(x,y) > S_{2w(m,n)}(x,y) \\
0 & \text{otherwise}
\end{cases}
\] (15)

IV. EXPERIMENTAL RESULTS AND DISCUSSION

In this section, detail of experiments which have been conducted to evaluate the performance and the validity of the proposed scheme is presented. Grayscale images of (Lena, Mandrill, Pepper, and Man) of size 512×512 are used as test input images. Binary images of copyright logos (WM1) and @ (WM2) are used as watermarks. Fig. 4 shows all the test images and watermarks. The regions of interest (ROI) for watermark inserting are obtained using the canny edge detector, and two sub-images are formed from these selected significant blocks.

Fig. 4. Test images and watermarks

The watermarks are inserted into the host images using the proposed embedding procedure. In this work, Haar wavelet has been used for DWT operation. Multiple scaling factors (MSF) are used in the proposed algorithm to improve the robustness level while maintaining the visual quality of watermarked image at an acceptable level. However, for the sake of comparison, the performance of the scheme is also assessed using a single scaling factor (SSF). The PSO technique is adopted to find optimized scaling factors (SF), and its parameters \(C_1\) and \(C_2\) are
set to be 2. Whereas, due to computational burden the values for the number of particles and iteration are set to 20 and 100 respectively.

i. Imperceptibility analysis

The level of imperceptibility (i.e., the degree of similarity between watermarked and original image) is measured using Peak Signal to Noise Ratio (PSNR). For original host image $G$ and watermarked image $G_w$, the definition of PSNR is given as follows.

$$PSNR = 10\log_{10} \frac{\text{Max}(G(i,j))^2}{\frac{1}{MN} \sum_{i=1}^{M} \sum_{j=1}^{N} (G_w(i,j) - G(i,j))^2} \text{dB} \quad (16)$$

Where, $M$ and $N$ are the number of pixels in row and column of the image, respectively.

Fig. 5 shows watermarked images of Lena, Mandrill, Pepper, and Man, and the obtained PSNR results under attack free scenario are given in Table 1.

![Watermarked images](image)

Fig. 5 Watermarked images using WM1 and MSF

By merely looking Fig. 4 and Fig. 5, we can notice that there is no visual difference between watermarked and original images, and this proves that the proposed watermarking scheme is able to achieve a high level of imperceptibility. In the area of watermarking, the imperceptibility is said to be at an acceptable level when the obtained PSNR values are greater than or equal to 38 dB [16]. From Table 1, it is clear that the obtained PSNR results are much higher than that of the minimum acceptable level.

ii. Robustness analysis

Copyright protection and content authentication applications require a high level of robustness. A watermarking scheme is said to be robust if it provides a watermarked image such that the embedded watermark is able to withstand all the attacks performed and is extractable even after the attacks. In this paper, we have simulated eighteen different attacks using Matlab software to evaluate the robustness of the proposed algorithm. The attacks are Gaussian noise, salt & pepper noise, poison noise, speckle noise, median filtering, average filtering, low-pass filtering, Weiner filtering, rotation, cropping, resizing, least significant bit removing, motion blurring, row-column blanking, histogram equalization, gamma correction, JPEG compression and sharpening. In the subsequent section for the sake of convenience, these attacks are labeled as GN, SPN, PN, SN, MF, AF, LPF, WF, RT, CRP, RS, LBR, MB, RCB, HE, GC, JC, and SH respectively. Fig. 6 shows attacked watermarked Lena images.

After applying the attacks on watermarked images, the existence of the embedded watermark resisting the attacks are checked by extracting them using the proposed extraction procedure. Fig. 7 shows the extracted watermarks from attacked images. For brevity, the visual results of Lena and mandrill images are only shown. From the figure, it is clear that the quality of extracted watermarks is highly similar to the original watermarks. The degree of similarity between original and extracted watermark is measured using Normalized Correlation Coefficient (NCC), and it is computed as follows.

$$NCC = \frac{\sum_{i=1}^{p} \sum_{j=1}^{q} (W(i,j) - \mu)(W_E(i,j) - \mu_E)}{\sqrt{\sum_{i=1}^{p} \sum_{j=1}^{q} (W(i,j) - \mu)^2} \sqrt{\sum_{i=1}^{p} \sum_{j=1}^{q} (W_E(i,j) - \mu_E)^2}} \quad (17)$$

Where, $W$ and $W_E$ are original and extracted watermarks respectively; $p$ and $q$ are the dimensions of watermark image. $\mu$ and $\mu_E$ represent the mean of original and extracted watermarks. For a given applicable attack, if obtained NCC value of extracted watermark is closer to 1, then the scheme is said to be robust against that attack. However, NCC value is at an acceptable level if its value is equal to 0.75 or higher [16]. The NCC and PSNR results obtained under different attack condition are given in Table 2.

<table>
<thead>
<tr>
<th>Images</th>
<th>PSNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lena</td>
<td>Using SSF: 45.3155, Using MSF: 46.0184</td>
</tr>
<tr>
<td>Mandrill</td>
<td>45.9254</td>
</tr>
<tr>
<td>Pepper</td>
<td>45.0154</td>
</tr>
<tr>
<td>Man</td>
<td>44.7186</td>
</tr>
</tbody>
</table>
Fig. 6 Attacked watermarked Lena image: (a) Gaussian noise attack, (b) salt & pepper noise attack, (c) speckle noise attack, (d) histogram equalization, (e) gamma correction, (f) cropping attack, (g) rotation attack, (h) motion blurring attack, (i) poison noise attack, (j) row-column blanking

<table>
<thead>
<tr>
<th>Attacks</th>
<th>Extracted watermark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attack free (ATF)</td>
<td>Using SSF</td>
</tr>
<tr>
<td>Lena</td>
<td>Mandrill</td>
</tr>
<tr>
<td>WM₁</td>
<td>WM₂</td>
</tr>
<tr>
<td>WM₁</td>
<td>WM₂</td>
</tr>
<tr>
<td>WM₁</td>
<td>WM₂</td>
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<td>WM₁</td>
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<td>WM₁</td>
<td>WM₂</td>
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<tr>
<td>WM₁</td>
<td>WM₂</td>
</tr>
<tr>
<td>WM₁</td>
<td>WM₂</td>
</tr>
<tr>
<td>Gaussian Noise (GN) (µ=0, ν=0.001)</td>
<td>@</td>
</tr>
<tr>
<td>Salt &amp; pepper noise (SPN) (D=0.02)</td>
<td>@</td>
</tr>
<tr>
<td>Median filter (MF) (3x3)</td>
<td>@</td>
</tr>
<tr>
<td>Histogram Equalization (HE)</td>
<td>@</td>
</tr>
<tr>
<td>Gamma correction (GC) (γ=0.925)</td>
<td>@</td>
</tr>
<tr>
<td>Cropping (CRP) (more than 25% cropped)</td>
<td>@</td>
</tr>
<tr>
<td>Rotation (RT) (8°)</td>
<td>@</td>
</tr>
<tr>
<td>JPEG compression (JC) (QF=70%)</td>
<td>@</td>
</tr>
</tbody>
</table>
From the Table 2, it can be observed that improved PSNR and NCC values are obtained, and this confirms that the proposed algorithm is able to meet the imposed watermarking requirements. The results obtained using both SSF and MSF are higher than the minimum acceptable level. However, MSF, which are used to modify the coefficients for watermark embedding, provide improved performance compared to SSF and maintain best trade-off between imperceptibility and robustness.

<table>
<thead>
<tr>
<th>Attacks</th>
<th>PSNR and NCC result obtained from simulations using WM1 under different attacks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lena</td>
</tr>
<tr>
<td>PSNR</td>
<td>NCC</td>
</tr>
<tr>
<td>ATBF</td>
<td>45.2155</td>
</tr>
<tr>
<td>GN</td>
<td>43.2136</td>
</tr>
<tr>
<td>SPN</td>
<td>43.0724</td>
</tr>
<tr>
<td>MF</td>
<td>42.8066</td>
</tr>
<tr>
<td>HE</td>
<td>43.0473</td>
</tr>
<tr>
<td>GC</td>
<td>44.0236</td>
</tr>
<tr>
<td>CR</td>
<td>44.5381</td>
</tr>
<tr>
<td>RT</td>
<td>43.7870</td>
</tr>
<tr>
<td>JC</td>
<td>43.2569</td>
</tr>
<tr>
<td>AF</td>
<td>43.1991</td>
</tr>
<tr>
<td>LBP</td>
<td>42.0172</td>
</tr>
<tr>
<td>MB</td>
<td>43.0203</td>
</tr>
<tr>
<td>LBR</td>
<td>44.2967</td>
</tr>
<tr>
<td>SH</td>
<td>44.2524</td>
</tr>
<tr>
<td>RS</td>
<td>43.8120</td>
</tr>
<tr>
<td>WF</td>
<td>42.8730</td>
</tr>
<tr>
<td>PN</td>
<td>43.1454</td>
</tr>
<tr>
<td>SN</td>
<td>43.1083</td>
</tr>
<tr>
<td>RCB</td>
<td>43.0652</td>
</tr>
</tbody>
</table>
TABLE 3. OPTIMIZED MULTIPLE SCALES (MSF) FOR JP ATTACK.

<table>
<thead>
<tr>
<th>Cover image</th>
<th>PSNR</th>
<th>NCC (JP, QF=50)</th>
<th>Optimized MSF [α_k] for different ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>σ_1</td>
</tr>
<tr>
<td>Lena</td>
<td>43.2248</td>
<td>0.9895</td>
<td>0.1827</td>
</tr>
<tr>
<td>Mandrill</td>
<td>44.0518</td>
<td>0.9823</td>
<td>0.1930</td>
</tr>
<tr>
<td>Pepper</td>
<td>43.0512</td>
<td>0.9764</td>
<td>0.1941</td>
</tr>
<tr>
<td>Man</td>
<td>43.4125</td>
<td>0.9873</td>
<td>0.1515</td>
</tr>
</tbody>
</table>

Fig. 8 NCC values of extracted watermark for JPEG compression attack.

PSO algorithm has been used to get optimized MSF. In Table 3, the optimized MSF which provide an improved result for JPEG compression attack are given. Furthermore, we have examined the robustness of the proposed algorithm by applying JP attacks varying the degree of attack level. For JPEG compression attack, the watermarked image is compressed with different quality factors (QF) ranging from 10 to 95. The quality of watermarked image decreases when the value of QF decreases. The plot of the obtained NCC result versus QF is shown in Fig 8 using all the test images. As can be seen from the plot, the NCC values are higher than 0.85 and this indicates that the proposed algorithm is robust for JPEG compression attack.

In the case of filtering attack, Median filter, average filter, low pass filter and Wiener filter of window size DxD are used. The value for D ranges from 3 to 15. The filtering attack causes blurring effect on the watermarked image. The bar plot of NCC values of the extracted watermark are shown in Fig 9 (a-d).
From Fig. 9, it can be observed that highest NCC values are obtained, and this proves that the proposed scheme is able to extract embedded watermark even after the watermarked image is severely degraded by applied filtering attacks. This proves that the proposed scheme is strongly robust to filtering attack.

In general, the overall results clearly confirm that the proposed watermarking scheme is able to achieve improved PSNR and NCC against various attacks condition.

V. CONCLUSION

Digital image watermarking scheme based on DWT, SVD, and PSO techniques is proposed in this paper. Regions of host image with the highest number of edge pixels are selected as the best location for watermark embedding. PSO algorithm provides best-optimized scaling factors which can give advanced robustness and imperceptibility. The experimental results show that the proposed scheme satisfies the imposed robustness and transparency requirements and this makes it more preferable for multimedia security applications.

REFERENCES


