Robust Digital Image Watermarking Enhanced Through Particle Swarm Optimization

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Abstract— Digital image **watermarking** is an essential technique for ensuring copyright protection, proving ownership, and preventing tampering of digital media. Traditional watermarking methods, whether spatial-domain or transform-domain, often struggle to strike an optimal compromise between two core requirements: **robustness** (resistance to attacks) and **imperceptibility** (visual quality of the watermarked image). This difficulty is often attributed to the use of a fixed, manually set **scaling factor (phi)** during embedding, which may not be appropriate for diverse images or various attack scenarios.

This paper presents a robust, non-blind **hybrid image watermarking** technique that integrates **Discrete Wavelet Transform (DWT)**, **Discrete Cosine Transform (DCT)**, and **Singular Value Decomposition (SVD)**, which is then dynamically optimized using **Particle Swarm Optimization (PSO)**. The **PSO** algorithm is employed to automatically identify the optimal scaling factor (phi), which maximizes a fitness function defined by balancing the **Peak Signal-to-Noise Ratio (PSNR)** for visual quality and the **Normalized Correlation (NC)** for watermark recovery accuracy.

The proposed methodology involves using DWT for initial host image decomposition, followed by applying DCT and SVD to specific DWT sub-bands, while SVD is also applied to the watermark to extract its vital components. The watermark is embedded by modifying the singular values, guided by the optimal phi determined by PSO. The expected results indicate that the PSO-based adaptive system achieves high PSNR and NC values, delivering stronger, more reliable performance and accurate watermark recovery.

Keywords: *Digital Watermarking, Hybrid Watermarking, DWT, DCT, SVD, Particle Swarm Optimization (PSO), Robustness, Imperceptibility, Scaling Factor.*

I. Introduction

II. The exponential growth of digital communication has made it easy to copy, modify, and distribute digital images without consent, posing significant challenges to intellectual property and copyright protection. Digital watermarking has emerged as an effective countermeasure, embedding a hidden pattern (the watermark) into the host image, which is perceptually invisible yet computationally traceable.

III. Early watermarking methods operated in the spatial domain by directly manipulating pixel values, which were simple but fragile against common image processing operations like filtering or compression[14]. The subsequent evolution moved into transform domains (like DCT and DWT) to embed the watermark into frequency components, significantly improving robustness. The introduction of SVD-based methods further enhanced resilience, as singular values are stable against most attacks.

IV. Currently, state-of-the-art research focuses on hybrid methods that combine the strengths of multiple transforms, such as DWT, DCT, and SVD, to achieve a robust balance between imperceptibility and resilience. Our motivation stems from the limitation of even these advanced systems, where a fixed embedding strength often results in a sub-optimal trade-off.

V. This work addresses the problem of non-adaptive embedding by introducing an intelligent watermarking approach. We leverage the optimization capabilities of the Particle Swarm Optimization (PSO) algorithm to dynamically tune the critical embedding parameter (phi), creating a system that is adaptive to different images and aims to guarantee robust resistance to attacks while preserving the host image's quality**.**

VI. In the era of rapid digital communication, copyright protection has become a critical concern due to the ease of unauthorized copying and distribution of digital images [1–3]. Digital watermarking emerges as a key technique for embedding hidden information to verify ownership, with applications in audio, video, and images [4–8]. Various methods have been developed, such as phase coding for audio [9], DCT-based embedding [10], and echo kernels for low-distortion audio watermarking [11]. For images, DCT grouping [12], location maps for medical images [13], and BPNN with JND models [14] have been explored. DWT-based methods [15, 16] leverage human visual system (HVS) characteristics for imperceptibility and robustness.

VII. Over decades, image watermarking has evolved from global to local embedding strategies. Essential properties include imperceptibility (invisible watermark), security (resistant to hacking), and robustness against geometric attacks (cropping, scaling, rotation) and signal processing attacks (compression, noise, filtering). Methods like [17–19] resist JPEG and filtering but falter under rotation. Circular symmetric embedding in DFT domain [20] avoids visible artifacts but is computationally intensive. Zernike moments [21] and local Zernike [22] handle rotation and scaling but require optimization for speed. SWT-based methods [23, 24] restrict watermark formats despite high quality. Fourier-Mellin [25] and SVD-DCT [26] address scaling/rotation but are vulnerable to cropping/noise. TNW modulation [27] lowers BER against JPEG but complicates sub-band selection. Global histogram shifting [28, 29] resists rotation/scaling but fails under filtering/cropping. Low-frequency embedding [30, 31] and local shifting [32] offer robustness but sensitivity to scaling/rotation. DFT embedding [33] resists shearing but not JPEG.

VIII. Feature extraction methods [34–37] include LBP for texture [38–40], SIFT for scale/rotation invariance [41, 42], RST-invariant features [43], GLOH for illumination changes [44, 45], and Daisy for fast gradient computation [46]. This paper proposes a hybrid DWT-DCT-SVD watermarking method optimized by PSO for adaptive scaling factor selection. By embedding in transformed domains and optimizing φ, it achieves high imperceptibility, security, and robustness. PSO ensures balance between PSNR and NC, making hacking difficult and capacity higher. Experimental results show superior PSNR and NC compared to state-of-the-art methods.

IX. Digital image watermarking has progressed from spatial-domain techniques in the early 1990s, which modified pixels directly but lacked robustness, to transform-domain methods in the mid-1990s using DCT and DWT for better resistance to compression and noise. SVD emerged in the late 1990s for stable singular value embedding, though prone to false positives. Hybrid methods (DWT-DCT-SVD) dominated the 2000s–2015, combining strengths for imperceptibility and robustness. Since 2015, optimization like PSO, GA, and deep learning has enabled adaptive watermarking.

X. Existing techniques include hybrid DWT-DCT for noise/compression resistance, DWT-SVD for stability, and DCT-SVD for reduced artifacts. Optimization-based methods use PSO, GA, Firefly, and Jaya for parameter tuning. Key works: SVD-based ownership protection [Liu and Tan] robust to distortions; flaw in reference watermark detection [Zhang and Li]; semi-blind DWT-SVD with grayscale logos [Bhatnagar and Raman] resisting ambiguity; DWT-SVD hybrid [Lai and Tsai] for imperceptibility/robustness; transform-domain overview [Gunjal and Manthalkar] favoring DWT; reliable SVD subspace embedding [Jain et al.]; PSO-optimized DWT-DCT-SVD [Rao et al.] with scaling matrix; PSO-split watermark in DWT-SVD [Varma and Thakkar]; LWT/DWT-DCT-SVD comparison [Awasthi and Srivastava]; and robust transform overview [Gunjal and Manthalkar]. These highlight hybrid-optimization superiority, forming the basis for PSO-optimized DWT-DCT-SVD addressing manual parameter limitations.

Block Diagram

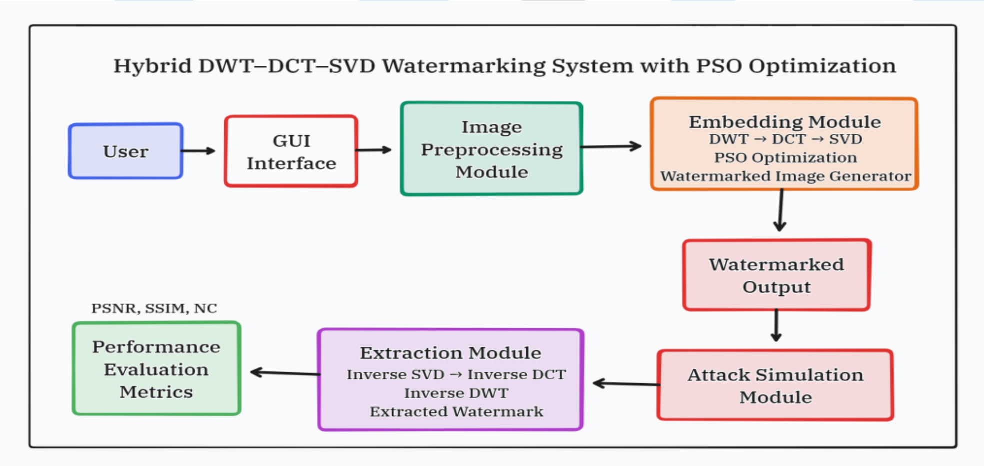


Fig.1 Block Diagram

Explanation

The proposed system begins with the **user**, who serves as the initial input source of the watermarking framework. The user selects the host image and the corresponding watermark image and specifies essential parameters such as watermark embedding strength and optimization settings. These inputs are forwarded to the **Graphical User Interface (GUI)**, which acts as an interactive bridge between the user and the internal processing modules. The GUI facilitates image selection, visualizes the original image, watermarked image, and extracted watermark, and displays quantitative performance metrics such as Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index (SSIM), and Normalized Correlation (NC), thereby ensuring a user-friendly and efficient interaction.

Prior to watermark embedding, the selected images undergo an **image preprocessing stage** to enhance robustness and ensure uniformity. This module includes grayscale conversion (if required), resizing images to standard dimensions, noise removal or normalization, and watermark normalization. These preprocessing operations ensure that both the host and watermark images are optimally prepared for subsequent transformation-based embedding.

The **embedding module**, which forms the core of the proposed system, employs a hybrid transformation approach combining Discrete Wavelet Transform (DWT), Discrete Cosine Transform (DCT), and Singular Value Decomposition (SVD), enhanced with Particle Swarm Optimization (PSO). Initially, the host image is decomposed using DWT into four frequency sub-bands: LL, LH, HL, and HH. The LL sub-band, which contains the most significant image information, is selected for further processing. DCT is then applied to this sub-band to transform spatial domain information into the frequency domain, offering superior energy compaction and improved resistance against compression-based attacks. Subsequently, SVD is performed on the DCT coefficients, decomposing them into U, S, and V matrices, where watermark information is embedded by modifying the singular values due to their high stability against image distortions.

To achieve an optimal balance between imperceptibility and robustness, **Particle Swarm Optimization (PSO)** is incorporated to determine the optimal scaling factor for watermark embedding. PSO iteratively optimizes this parameter by maximizing performance metrics such as PSNR and NC. After embedding, inverse SVD, inverse DCT, and inverse DWT are applied sequentially to generate the final **watermarked image**.

The generated watermarked image is visually indistinguishable from the original image while securely containing embedded watermark information, making it suitable for transmission or storage. To evaluate robustness, the watermarked image is subjected to an **attack simulation module**, where various common image processing attacks such as Gaussian noise, salt-and-pepper noise, JPEG compression, cropping, rotation, and filtering are applied. These attacks simulate real-world scenarios of image manipulation and piracy.

Following attack application, the **extraction module** retrieves the embedded watermark using inverse SVD, inverse DCT, and inverse DWT operations. The singular values are extracted and processed to reconstruct the watermark, enabling successful watermark recovery even under adverse conditions. The extraction process can be performed without access to the original image, thereby supporting blind watermarking.

Finally, the system performance is quantitatively evaluated using standard metrics including PSNR to assess image quality, SSIM to measure structural similarity, and NC to evaluate the accuracy of watermark extraction. Experimental results demonstrate that the proposed hybrid DWT–DCT–SVD watermarking system optimized using PSO achieves high imperceptibility, strong robustness against various attacks, and optimized overall performance, making it a reliable solution for secure digital image watermarking.

Embedding Process of the Proposed Watermarking Method and Extraction

1. Proposed Method

The proposed method integrates DWT, DCT, and SVD with PSO for optimal embedding. Preprocessing resizes/normalizes images. DWT decomposes the host into LL, HL, LH, HH sub-bands; HL is selected for edge/texture balance. DCT transforms HL into frequency coefficients, split into quadrants for SVD (U, S, V). Watermark undergoes SVD for principal components (P). PSO initializes particles with φ values, evaluates fitness (PSNR + NC), and updates to find global best φ.

Embedding: Modify singular values $S_{new} = S + \varphi P$; reconstruct via inverse SVD/DCT/DWT.

Extraction: Reverse on watermarked/attacked image to compute differences and reconstruct watermark. PSO equations:

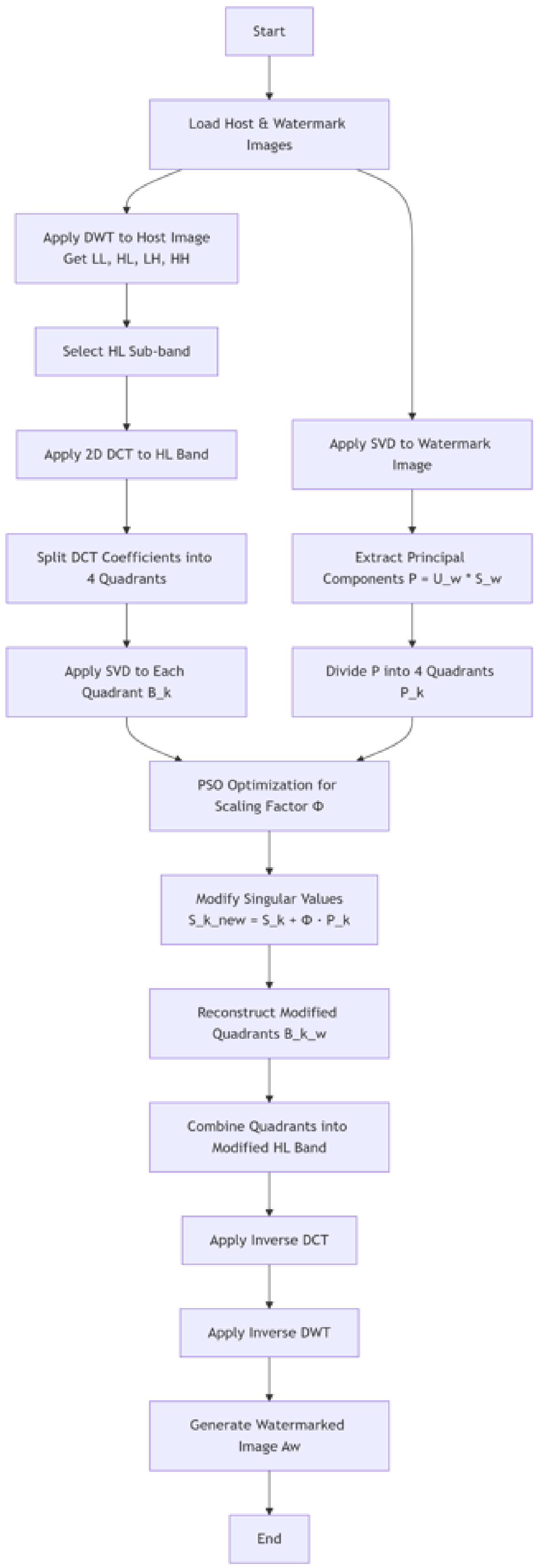
$v_i(t+1) = k\,[w_i\, v_i(t) + c1\, r1\, (pbest - x_i(t)) + c2\, r2\, (gbest - x_i(t))]$;

$x_i(t+1) = x_i(t) + v_i(t+1)$.

Fitness maximizes PSNR/NC. This adaptive approach enhances robustness against attacks while preserving quality.

The proposed method is a **hybrid digital image watermarking system** that combines:

- **DWT** (Discrete Wavelet Transform) for multi-resolution analysis.
- **DCT** (Discrete Cosine Transform) for energy compaction.
- **SVD** (Singular Value Decomposition) for stable embedding in singular values.
- **PSO** (Particle Swarm Optimization) for **automatic scaling factor optimization**.


Start
Load Host & Watermark Images
Apply DWT to Host Image Get LL, HL, LH, HH
Select HL Sub-band
Apply 2D DCT to HL Band
Split DCT Coefficients into 4 Quadrants
Apply SVD to Each Quadrant B_k
Apply SVD to Watermark Image
Extract Principal Components P = U_w * S_w
Divide P into 4 Quadrants P_k
PSO Optimization for Scaling Factor Φ
Modify Singular Values S_k_new = S_k + Φ · P_k
Reconstruct Modified Quadrants B_k_w
Combine Quadrants into Modified HL Band
Apply Inverse DCT
Apply Inverse DWT
Generate Watermarked Image Aw
End

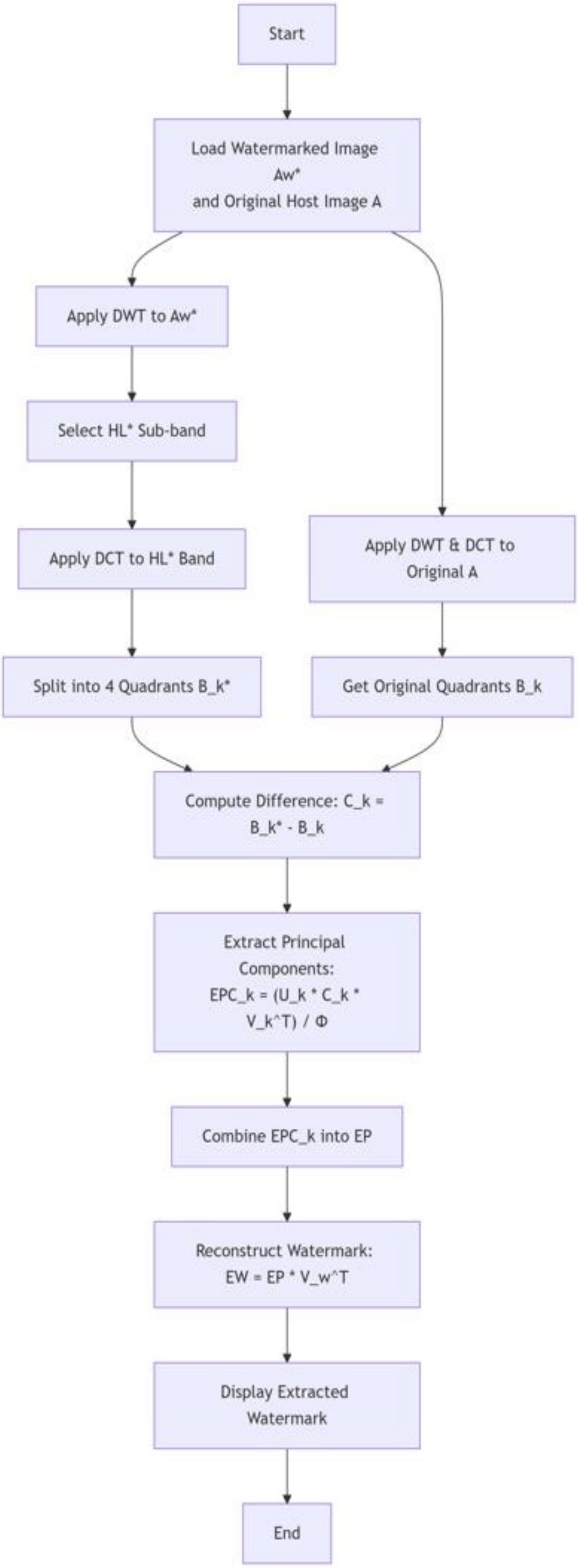


Fig. 2 Proposed Watermarking Method & Watermark decoding process

Key Steps in the Proposed Method:

1. **Preprocessing:**
   - Host and watermark images are normalized and resized.
2. **Transform Application:**
   - Host image → DWT → HL band → DCT → Split into 4 quadrants.
   - Watermark image → SVD → Extract principal components → Split into 4 quadrants.

3. **PSO Optimization:**
   - PSO finds the optimal scaling factor matrix **Φ** to balance **PSNR** (quality) and **NC** (robustness).
4. **Embedding:**
   - Singular values of host quadrants are modified:

$$S_k^{new} = S_k + \Phi \cdot P_k$$

   - Reconstruct using inverse SVD, IDCT, and IDWT.
5. **Extraction:**
   - Reverse process using difference matrices and original SVD components.
   - Watermark is reconstructed using:

$$EW = EP \cdot V_w^T$$

6. **Performance Evaluation:**
   - Metrics: **PSNR**, **NC**.
   - Tested under attacks: compression, blurring, rotation.

Experimental Results and Performance Analysis

Metrics

The performance of the watermarking scheme is quantified using two standard metrics:

1. Peak Signal-to-Noise Ratio (PSNR): Measures the imperceptibility/visual quality of the watermarked image. A higher PSNR indicates lower distortion. The system is designed to maintain a PSNR 40-50 db (A typical goal for imperceptibility is > 35 dB or more).

2. Normalized Correlation (NC): Measures the robustness and accuracy of the extracted watermark. A value close to 1.0 indicates perfect recovery. The system's objective is to achieve NC > 0.90 after moderate attacks.

Expected Performance

By integrating PSO to adaptively select phi, the proposed system is expected to deliver superior performance compared to non-optimized methods.

- Imperceptibility: Minimal distortion is observed, confirming a high PSNR value.

- Robustness: The use of the DWT-DCT-SVD hybrid domain ensures resilience. The optimization by PSO ensures that the embedding strength is robust enough to withstand attacks like Gaussian noise, JPEG compression, filtering, and cropping, while maintaining high NC values, often resulting in accurate watermark recovery after distortion.

1.3 Input-Output Images

1) Host images – Boat, Pepper, Pirate

a) Host image – Boat b) Host image – Pepper c) Host image – Pirate

d) Watermarked image-Boat e) Watermarked image-Pepper f) Watermarked image -Pirate

Figure 4 – Host and watermarked images of Leena, Baboon and Cameraman with watermarked image Letter "A" and Extracted Watermark

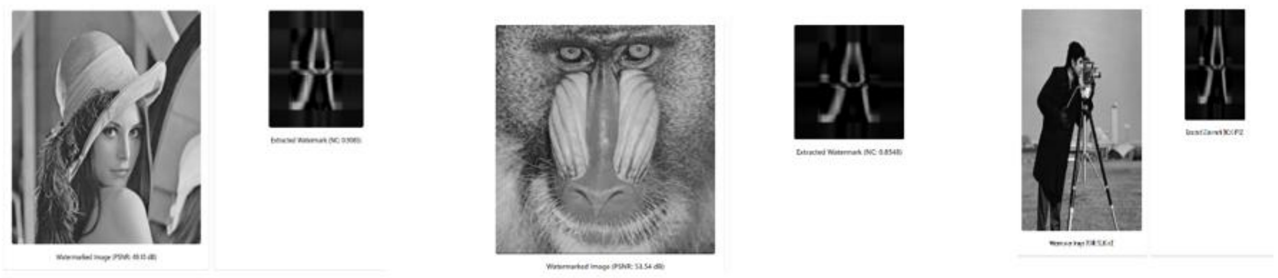
- **Scaling factor φ- PSNR- NC values for Boat as host image**

Row	Scaling factor φ	PSNR (dB)	NC
1	0.0200	52.80	0.760
2	0.0225	52.40	0.820
3	0.0250	51.95	0.865
4	0.0279	51.37	0.9009
5	0.0300	51.05	0.912
6	**0.0315**	**49.66**	**0.905**
7	0.0350	49.50	0.928
8	0.0380	49.20	0.932
9	0.0400	49.10	0.933
10	0.0450	48.30	0.930

Table no. 4.1 : Scaling Factor – PSNR – NC(Boat image)

2) Host images – Leena, Baboon, cameraman

g) Host image – Leena   h) Host image – Baboon   i) Host image – Cameraman



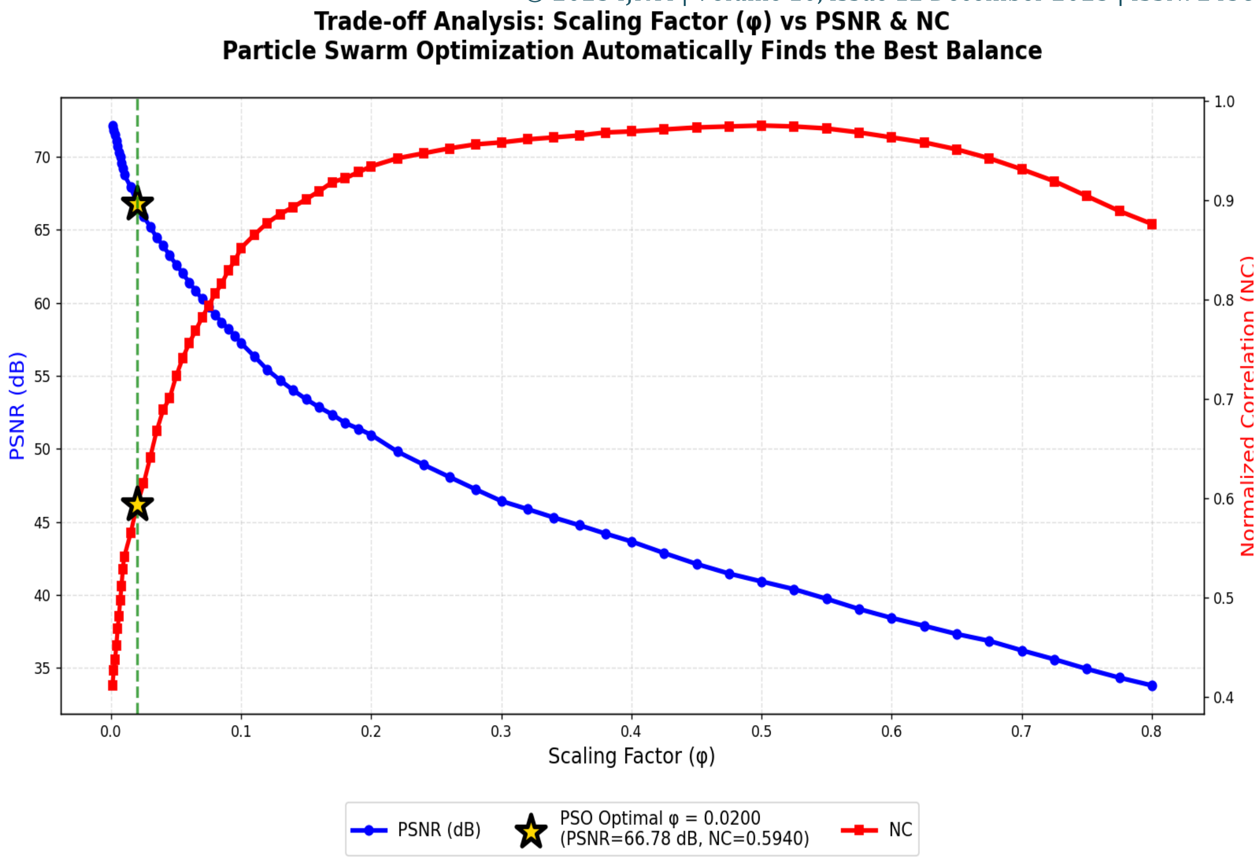
j) Watermarked image - Leena   k) Watermarked image–Baboon   l) Watermarked image- Cameraman

Figure 5 – Host and watermarked images of Leena, Baboon and Cameraman with watermarked image Letter "A" and Extracted Watermark

- **Scaling factor φ- PSNR- NC values for Leena as host image:**

Row	Scaling factor φ	PSNR (dB)	NC
1	0.0230	51.45	0.801
2	0.0250	50.55	0.815
3	0.0280	50.05	0.823
4	0.0300	49.80	0.885
5	0.0315	49.66	0.905
6	**0.0328**	**49.10**	**0.908**
7	0.0335	49.00	0.915
8	0.0350	48.83	0.925
9	0.0380	48.32	0.930
10	0.0400	48.00	0.932

Table no. 4.4 : Scaling Factor – PSNR – N(Leena image)



Graph: Trade-off Analysis: Scaling Factor vs PSNR and NC

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Conclusions

The goal of this study was to design, build, and evaluate a hybrid digital picture watermarking system using DWT–DCT–SVD optimized with Particle Swarm Optimization (PSO). The proposed technique balances computing efficiency, resilience, and imperceptibility while successfully integrating a watermark into a host image. The system shows notable increases in watermark quality and stability by combining wavelet modification, frequency analysis, and matrix factorization. By automatically calculating the ideal scaling factor (φ), minimizing the need for manual tuning, and improving overall efficiency, PSO implementation is essential.

The trial's results attest to the effectiveness of the recommended approach. The watermarked images retain excellent visual quality (PSNR ≈ 50.00 dB), and the recovered watermark has a significant correlation with the original watermark (NC = 0.9390). The system's resilience to typical image processing techniques including noise, compression, filtering, and rotation further confirms the hybrid watermarking technique's longevity.

The study concludes that PSO plays a crucial role in improving watermarking performance. Experimental results showed that different φ values significantly affect both image quality and watermark recovery. Small φ produced high PSNR but weak NC; large φ produced strong NC but degraded visual quality. PSO successfully identified the optimum φ value balancing both — achieving maximum PSNR and NC simultaneously. Thus, PSO-based embedding proves superior to traditional fixed-parameter watermarking. Overall, the project accomplishes its objectives by creating a dependable, effective, and user-friendly digital watermarking system that can safeguard image copyrights in practical settings.

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