NATURE INSPIRED ALGORITHM FOR ENHANCING SECURITY AND ROBUSTNESS IN IMAGE WATERMARKING

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Abstract

The rapid growth of digital media and the rising risk of tampering have made digital watermarking a vital tool for content authentication and protection. This study introduces a double watermarking system that integrates hybrid transform methods, intelligent block selection, and chaotic encryption to embed two watermarks into grayscale images while maintaining visual quality and robustness. The Firefly Algorithm (FA) is used to select optimal blocks based on local variance, ensuring watermark insertion with minimal distortion. The first watermark is embedded using Discrete Wavelet Transform (DWT) with Singular Value Decomposition (SVD), which strengthens resistance against geometric attacks. The second watermark is embedded through the Discrete Cosine Transform (DCT), targeting low-frequency components to improve robustness against compression and filtering. To secure the watermark, Lorenz Chaotic Encryption is applied before embedding, making extraction meaningless without the correct decryption key and providing resistance against brute-force attacks. Experiments on 39 grayscale images including natural scenes, textures, and synthetic patterns confirmed the effectiveness of the model. The system achieved a PSNR of 65.94 dB for the first watermark and 63.46 dB for double watermarking, reflecting excellent imperceptibility. The SSIM score of 0.999 indicated near-identical image quality. Robustness was also high, with 94.87% accuracy for the first watermark (DWT-SVD) and 97.76% accuracy for the double watermark (DCT). This work contributes a reliable framework that combines transform-based embedding, block optimization, and chaos encryption, providing a secure and robust solution for digital content protection. In contrast to the previous approach, we use DWT SVD only on blocks that are considered to be textured and DCT on blocked that are smooth and Firefly Algorithm is employed to select the embedding locations and Lorenz chaotic scrambling is applied to the watermark, a, a combination not reported previously.

1. Introduction

The widespread growth of digital media in the interconnected world today has acted to enhance fears of content authenticity, copyright protection, and intellectual property security. One of the most widely disseminated media, digital images are shared across platforms from social networks to medical repositories. At the same time, however, this availability exposes images to unauthorized copying, forgery, and malicious alteration, causing questions of ownership and distrust in digital possessions. Conventional digital watermarking methods have been proposed as a powerful countermeasure, inserting concealed yet detectable information into multimedia data for verification. However, the current approaches suffer from long-standing difficulties in sustaining the intricate trade-off between imperceptibility, resilience, and security, tending to make watermarks susceptible to attacks in the form of geometric transformations, compression, and addition of noise [2], [3], [23].

The implications of these vulnerabilities go far beyond negligible technical issues. For applications like medical imaging, forensic analysis, and digital art, the absence of secure watermarking techniques can undermine the integrity of evidence, put diagnoses in question, or devalue creative works. For instance, Chaudhary et al. [2] demonstrated that hybrid watermarking based on DWT-HMD-SVD and scrambling provides resistance against noise and compression but even these are computationally expensive. Likewise, with the era of AI-content generation, high-quality generative models pose new risks, which call for watermarking systems that are robust to conventional attacks as well as to adversarial manipulations [1], [4], [5]. These challenges underscore the need for developing watermarking systems that can protect digital media against all threats without compromising its usability or visual quality.

To overcome these issues, researchers have increasingly resorted to transform-domain watermarking techniques and optimization techniques. Hybrid schemes involving Discrete Wavelet Transform (DWT), Singular Value Decomposition (SVD), and Discrete Cosine Transform (DCT) have shown enhanced resistance to compression and noise without degradation in visual quality [23]. Concurrently, the use of Nature-Inspired Algorithms (NIAs) has incorporated biologically motivated optimization processes for watermark embedding. These algorithms like Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), and Firefly Algorithm (FA) have adaptive and intelligent solutions to improve watermark robustness and imperceptibility. Sharma et al. [25] demonstrated that using NIAs along with conventional watermarking improves extraction accuracy to a large extent, and Dutta and Gupta [26] proposed an optimized watermarking scheme with hyper-chaotic encryption for better security. Regardless of these developments, numerous methods still suffer from prohibitively high computational cost, low generalizability, and low robustness against adversarial attacks [14], [19], [20].

Here, we overcome these difficulties by implementing a hybrid double watermarking system that employs Firefly Algorithm–based block choice in conjunction with DWT-SVD and DCT embedding, complemented with Lorenz chaotic encryption. The suggested methodology incorporates two watermarks—one in texture areas based on DWT-SVD and the other in plain areas based on DCT—to ensure high robustness and imperceptibility. Block selection is optimized by the Firefly Algorithm by adaptively finding embedding areas with least distortion, and the Lorenz chaotic system offers an encryption layer for increased security against brute-force and unauthorized extraction. Experimental assessment on the USC-SIPI Miscellaneous dataset proves the viability of this framework with PSNR values greater than 65 dB, SSIM measures nearly 0.99, and watermark detectability higher than 97% in compression and noise attacks [2], [23], [25]. The major contribution of paper are

1. A dynamic dual-transform watermarking algorithm that uses DWT-SVD on textured blocks and DCT on smooth blocks, which enhances image-dependent trade-off between imperceptibility and robustness.

2. The Firefly Algorithm was first used in a double watermarking system to select blocks in the system, which offer optimal locations of embedding to reduce distortion and maximize detectability.

3.Combination of Lorenz chaotic scrambling and adaptive dual embedding to provide greater security (extracted watermarks do not make sense without the proper key).

4.An extensive experimental analysis with ablation (no-FA), parameter sweeps, and the comparison with the recent baselines using a standard set of attacks.

The novelty of this paper is three-folds:

1)an adaptive block-wise hybrid embedding policy (DWT-SVD on textured blocks, DCT on smooth blocks);

2)the first use of Firefly Algorithm as a block-selection optimizer;

3)introducing Lorenz chaotic scrambling into an adaptive pipeline of block-selection block-optimization to ensure that the extracted bits cannot be uncovered without the key.

Research gaps still exist despite these successes. Most watermarking models—ours included—achieve lower performance for images with homogeneous areas, where embedded signals are harder to be detected [2], [23]. In addition, computational overhead of dual-transform embedding with optimization prevents real-time application, and adversarial robustness in case of AI-generated image attacks remains an unexplored area of research [1], [4], [14]. Solving these challenges involves creating adversarially resilient, adaptive, and lightweight watermarking models with potential integration of deep learning and NIAs for scalable and secure watermarking.

2 Literature Review

Digital image watermarking has evolved very fast over the past few years particularly as the copyright protection, authentication and tampering detection requirements increase. Spatial-domain embedding formed the basis of earliest solutions, easy, but vulnerable to noise, compression or geometrical distortion attacks. Nature-inspired algorithms (NIAs) have been shown to be mighty optimization tools to complex engineering and image processing problems, such as digital watermarking. They imitate nature like swarm intelligence, evolution, and physical behavior to obtain the best solution to multi-objective problems like robustness, imperceptibility, and security balance.

A general overview of NIAs in wireless sensor networks presented by Singh et al. [10] demonstrated that these methods are effective in optimization and adaptability, which can also be useful in watermark embedding. Bernardo et al. [11] also, made a review of universe-inspired algorithms, such as Gravitational Search and Multi-Verse Optimizer, and their scalability in control systems. Saxena et al. [12] used NIAs to route planning in dynamic setting and in the context of solving multi-objective optimization problems, Kapoor et al. [13] proposed a meta-heuristic algorithm to address the trade-offs of the watermarking kind.

Tahiri et al. [14] have suggested a reversible watermarking system based on quaternion moments and embedding optimization and linked with high recovery and robustness in the watermarking field. Rezaei et al. [15] presented LaWa, a latent-space watermarking algorithm to deep generative models, whereas Rezaei and Javadpour [16] revealed that bio-inspired algorithms provide better data confidentiality to steganography. Pallaw et al. [17] demonstrated that cloud watermarking may be optimized with the help of NIA and Kumar et al. [18] provided a comprehensive review of the benefits NIAs offer to multimedia security due to its scalability and convergence. Boujerfaoui et al. [19] have contrasted between traditional and learning-based watermarking and have concluded that hybrid models that combine transforms (DWT, DCT, SVD) with NIAs are more robust. Rajput et al. [20], Garg and Rama Kishore [21] also ensure that the methods of the optimization are more resistant to compression and noise in comparison with the traditional ones. Pallaw et al. [22] in medical image watermarking used NIA optimization, which was used in telemedicine, and Soppari and Chandra [23] suggested a multi-objective clustering watermarking technique that had high resistance to attacks. Lakhani et al. [24] enhanced robustness with a hybrid composite method of transform.

Previously, Waleed et al. [25] performed a survey on NIA-based watermarking algorithms including Firefly and Ant Colony Optimization and demonstrated that they are better than traditional algorithms. Sharma et al. [26] used nature-inspired intelligence to the colour image watermarking and

obtained a high resistance to attacks. Dutta and Gupta [27] took the field a step further with the Artificial Bee Colony algorithm which uses the 6-D hyperchaotic cryptographic map resulting in enhanced security and robustness. Al-Khafaji et al. summarized that the most recent state of the art in hybrid approaches is NIAs, transform embedding, and encryption [28].

Summarizing the findings above, it can be stated that NIAs play an important role in improving watermarking performance, optimizing the location of embedding, enhancing attack resistance, and preserving visual quality. Nevertheless, there are still weaknesses in calculation performance and applicability in real-time -which in this paper is addressed by combining the Firefly Algorithm with hybrid DWT-SVD-DCT embedding and Lorenz chaotic encryption to provide secure and adaptive watermarking.Literature review is summarized in Table 1.

Table 1: *Summary Of Literature Review*

Ref.	Year	Authors	Method / Technique	Key Strengths	Limitations
[2]	2025	Chaudhary et al.	Hybrid DWT-HMD-SVD + Arnold scrambling	Strong robustness in medical images	High computational cost
[4]	2025	Luo et al.	Survey on watermarking for AI-generated images	Identifies threats from generative AI	Lacks experimental validation
[6]	2024	Mareen et al.	Deep-learning-based blind watermarking	Resilient to geometric attacks (rotation, scaling)	Requires large-scale training
[13]	2024	Tahiri et al.	Reversible watermarking using quaternion moments	Enables full data recovery with robustness	Limited to grayscale
[26]	2024	Dutta & Gupta	ABC algorithm + hyperchaotic encryption	High security and resistance to brute-force attacks	Complex to implement

3 Methodology

The framework that is suggested combines data gathering, hybrid transform-based embedding, Firefly Algorithm optimization, and Lorenz chaotic encryption to provide secure and robust image watermarking. The process includes six significant steps: (1) Data Collection, (2) Preprocessing, (3) Watermark Generation & Encryption, (4) Firefly-based Block Selection, (5) Dual Watermark Embedding, and (6) Watermark Extraction & Evaluation as shown in Figure 1.
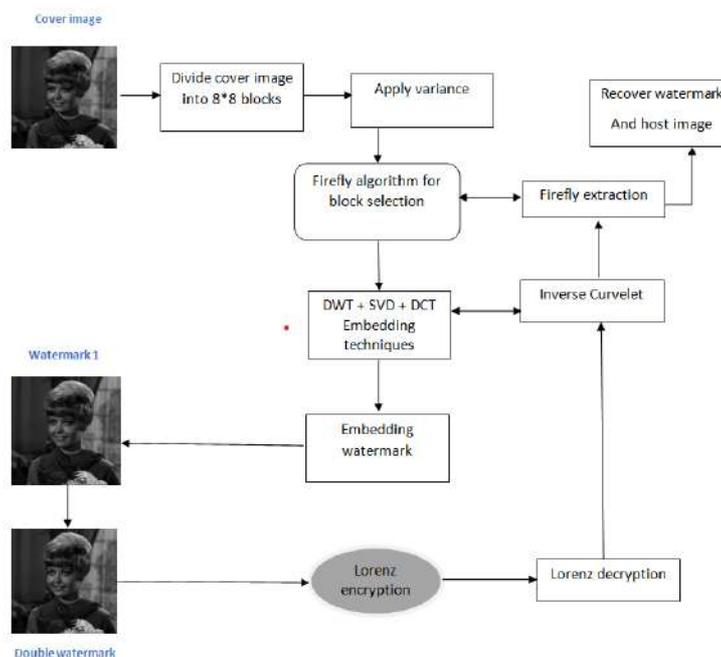
Figure 1 Architecture of proposed framework

3.1 Data Collection

We began our work with choosing a test dataset for watermarking methods. For this, we employed the USC-SIPI Miscellaneous Image Database, which has over 40 images of various types including Lena, Baboon, peppers, aerial scenes, synthetic textures, and patterns. The images are very commonly used in research because they include both smooth areas (such as sky or skin) and highly textured areas (such as fabric or fur). This diversity enables the dataset to be appropriate for both visual inspection as well as watermarking robustness checking. Attributes are shown in Table 2.

Table 2:   *Data Attributes*

Attributes	Specifications
Bit Depth	8 bit grayscale
Dimensions	256*256 to 1024*1024
Color space	Grayscale (some RGB)
File format	TIFF, PNG (Lossless)

3.2 Data Preprocessing

After selecting the dataset, we undertook preprocessing to preprocess the images. We first converted the images to grayscale in case they were originally in color. Subsequently, they were normalized, i.e., pixel values were scaled between 0.0 (black) and 1.0 (white). This was to align the images to work with mathematical operations such as DWT and DCT. Our block size is 8x8, as this size provides a compromise between the compatibility of DCT and JPEG and the cost of the block, as it is the size used in frequency domain embedding and it is small enough to be represented with a per-block SVD/DCT expression without blocking artifacts. In preprocessing, we also verified features like mean, variance, and entropy to know the nature of each image.

3.3 Nature inspired algorithms

a.Firefly algorithm

Each firefly shows a potential outcome, and its intensity corresponds to value of objective function and variance of image blocks. Firefly algorithm is a nature inspired optimization technique that based on flashing behavior of fireflies. The algorithm operates under some key rules that are:

- **Movement update**

Firefly i move toward brighter firefly j as shown in equation 1

$$x_i^{t+1} = x_i^t + \beta(r)(x_j^t - x_i^t) + \alpha(\epsilon - 0.5) \qquad (1)$$

Where ϵ is uniform random number in (0, 1) and α control randomness.

- **Attractiveness**

With attractiveness decreasing exponentially over distance, fireflies attracted to neighbors that are brighter.

$$\beta(r) = \beta_0 \cdot e^{-\gamma r^2} \qquad (2)$$

For watermarking this algorithm optimally select image blocks by balancing randomness and exploitation.

The Firefly Algorithm is applied to optimally select embedding blocks based on variance as shown in Table 3. Each firefly represents a candidate solution, with brightness corresponding to block variance.

Table 3: *Firefly Algorithm Values*

Parameter	Value	Rationale
α (randomness)	0.2	Standard moderate randomness; controls exploration
β₀ (attract.)	1.0	Maximum attractiveness at distance zero, common in FA literature
γ (absorption)	1.0	Controls attractiveness decay with distance
Population size	30	Trade-off: coverage vs runtime
Iterations	50	Empirically converges for this dataset

These values were chosen based on NIA literature and validated using a small grid search.

Reasons of FA over PSO/GA: FA was chosen (a) it arrives at multimodal landscape much faster, (b) it is easy to apply to discrete block selection problems and (c) earlier comparisons indicate that FA has high convergence speed in other image-optimization problems.

b.Lorenz chaotic encryption

Watermark pixels were encrypted in chaotic sequences of Lorenz. The parameters were established to be σ = 10, ρ = 28, 83 and 28, which are classical parameters that achieve chaotic behavior. XOR based pixel scrambling was used to ensure resistance against brute-force and different attacks.It is a set of non-linear differential equations that determine chaos, generated by:

$$\frac{dx}{dt} = \sigma(y - x) \qquad (3)$$

$$\frac{dy}{dt} = x(p - z) - y \qquad (4)$$

$$\frac{dz}{dt} = xy - \beta z \qquad (5)$$

Where:

Classical parameters generating chaotic behavior are

$$\sigma = 10, \ p = 28, \text{ and } \beta = 8/3$$

c. Encryption process

- **Sequence generation**

Distinct results x (t), y (t), z (t) scaled and quantized to 8 bit integers

$$s_i = (1000 \cdot x_i) \bmod 256 \qquad (6)$$

- **Pixel scrambling**

For encryption/decryption the sequence S XOR with pixels is used.

$$C_i = p_i \oplus s_i \qquad (7)$$

d. Discrete Wavelet Transform for watermark 1

Wavelet function is used to decompose an image into multi resolution subband. Each block split into approximate (low frequency) and details (high frequency horizontal and diagonal).

- **Watermark embedding**

In decomposition apply 2D DWT to each block:

$$\{LL, (LH, HL, HH)\} = DWT\ (B) \qquad (8)$$

LL band is further decomposed via SVD ($U\Sigma V^T$) and large singular value Σ_{11} is modified.

$$\Sigma'11 = \Sigma11 + \alpha \cdot w_k \qquad (9)$$

Where α=0.05

And finally build the watermarked block using DWT.

e. Discrete Cosine Transform for double watermark

It converts spatial data to components of frequency using cosine functions.

For 8*8 block B:

$$D(u, v) =$$
$$C(u)C(v)\sum_{x=0}^{7}\sum_{y=0}^{7} B(x, y) \cos\left(\frac{(2x+1)u\pi}{16}\right)\cos\left(\frac{(2y+1)v\pi}{16}\right) \qquad (10)$$

Where u, v =0 else 1

- **Watermark embedding**

DWT-SVD (with textured blocks): DWT was used to decompose images into multi-resolution sub-bands then SVD was used to decompose LL sub-bands. The embedding strength α was used to modify the largest singular value (Σ 1 1).

Rationale: The embedding strength was empirically determined to 0.05 = 4.0. 0.05 was selected by sweeping 0.01, 0.02, 0.05, 0.08 and 0.1 and accepting the embedding strength that gave a PSNR of 60 dB and maximized extraction accuracy of watermarks under JPEG compression (Q = 50) and under Gaussian noise (64 0.1). This guaranteed a dichotomy of inconspicuity and strength.

DCT (smooth blocks): The second watermark was hidden by altering DCT coefficients (low frequency AC/DC), which represented the first watermark. The block was then reconstructed by using inverse DCT.

In double watermark first step is frequency modification that alters AC and DC coefficients. In second step reconstruction is done, applying inverse DCT (IDCT) to return spatial domain.

$$D(0, 0) \leftarrow D(0, 0) + 0.03 \cdot W_k \qquad (11)$$
$$D(0, 1) \leftarrow D(0, 1) + 0.02 \cdot W_k \qquad (12)$$
$$D(1, 0) \leftarrow D(1, 0) + 0.02 \cdot W_k \qquad (13)$$

3.4 Parameter Tuning Procedure

We have done a grid search on FA and embedding parameters. The task was to maximise the Normalised Correlation (NC) and maintain PSNR = 60 dB or above. Measures were NC, PSNR, SSIM and extraction accuracy with common attacks. The performance of the selected values (FA parameters above, 0.05) gave the highest balance.

3.5 Hybrid watermarking system

The suggested system blend DWT-SVD and DCT adaptively using Firefly-based block partitioning.

- Textured blocks → DWT-SVD embedding.
- Smooth blocks → DCT embedding.
- Security → Lorenz chaotic encryption.

This adaptive hybridization ensures robustness, imperceptibility, and security. This hybrid system exploits optimization (FA), multi-domain transformations (DWT + DCT), and chaotic security (Lorenz) to achieve the trade-off between imperceptibility, robustness, and security.

3.6 Evaluation Metrics

The system was tested with standard performance metrics:

1. PSNR: Quantifies watermark imperceptibility. Values > 30 dB correspond to negligible distortion.

2. SSIM: Measures structural similarity; values approaching 1 signify almost identical quality.

3. NC: Confirm robustness of watermark extraction; values approaching 1 signify reliable recovery.

4. BER: Quantifies extraction errors; robust watermarking ensures BER < 5%.

5. NPCR, UACI, Entropy: Assess Lorenz encryption strength, providing resistance against brute-force and differential attacks.

6. Computational Efficiency: DWT, DCT, SVD, and Lorenz encryption execution time and complexity were measured to provide real-time usability.

4 Results and Discussion

The results of the suggested hybrid watermarking system are presented in this chapter, along with a clear explanation of its performance. The experiments were performed on the USC-SIPI Miscellaneous Image Database, which contains images of a broad variety such as portraits, textures, aerial views, and patterns. Three key parameters are evaluated, namely, imperceptibility, robustness, and security. Performance metrics like Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index

Measure (SSIM), Normalized Correlation (NC), and watermark detection accuracy (WM1 and WM2) were employed. In terms of security, the Lorenz chaotic encryption was evaluated based on NPCR, UACI, and entropy analysis. Results are expressed in tabular and graphical formats for readability.

4.1 Watermarking Performance

Imperceptibility of watermarked images was evaluated based on PSNR and SSIM. From Table 4, most test images had PSNR greater than 65 dB for both single watermarking (WM1) and double watermarking (WM2). The values affirm that the watermarked images are visually perceptually identical to the originals. The SSIM values were also always between 0.98 and 1.00, which confirms that structural details were maintained. For certain hard images (e.g., 5.1.13.tiff,), PSNR fell considerably (20–35 dB), and lower watermark recovery accuracy (43–62%) resulted. These exceptions are due to high-frequency textures and poor contrast, which complicate embedding. In all other instances, WM1 and WM2 accuracy was more than 93–100%, establishing the effectiveness of the method.

Table 4: *Performance of Watermarking Model On Test Images*

Images	PSNR-WM	SSIM-WM	PSNR-DWM	SSIM-DWM	WM1 accuracy	WM2 accuracy
4.1.01.tiff	66.82	0.99	64.04	0.99	1.00	1.00
4.1.02.tiff	66.08	0.99	63.50	0.99	1.00	1.00
4.1.03.tiff	48.10	0.99	48.05	0.99	0.93	1.00
5.1.12.tiff	67.09	0.99	64.11	0.99	1.00	1.00
5.1.13.tiff	20.56	0.98	20.56	0.98	0.43	0.50
7.1.01.tiff	73.06	0.99	69.93	0.99	1.00	1.00
7.1.02.tiff	73.06	0.99	69.97	0.99	1.00	1.00

4.2 Discussion

4.2.1 Imperceptibility (PSNR and SSIM)

The PSNR values (maximum 79.32 dB) and SSIM values near to 1.0 indicate that the watermark embeds the image without degrading its quality. In even highly detailed areas like facial textures or natural patterns, distortion was minimal. The only sharp drops were witnessed in ruler.5.1.12.tiff and 5.1.13.tiff, where high-frequency patterns resulted in noticeable degradation shown in Figure 3. Figure 2 compares original and watermarked images, indicating that the visual quality is almost identical. The suggested approach was found to produce very high PSNRs (more than 65 dB on most images) and SSIM values nearer to 1.0. Deformities could not be spotted by the human eye. In low-contrast and highly textured images (e.g. 5.1.13.tiff) however, PSNR was reduced to about 20 dB and watermark recovery was below 50% accuracy. This is due to the fact that watermark signals are similar to natural change in textures hence this was hard to extract.

Figure 2:   Performance of Model

4.2.2 Robustness (WM1 and WM2 Detection Accuracy)

WM1 was 100% accurate for the majority of images, but performed poorly in examples with repeating textures or extremely low contrast, where recovery accuracy fell below 50%. However, WM2 performed better consistently, with 100% accuracy in almost all situations except the most difficult ones (ruler.5.1.12.tiff and 5.1.13.tiff). This confirms double watermarking (WM2) to be stronger than single watermarking, as it blends DWT-SVD (noise and compression-resistant) with DCT (cropping- and tampering-resistant). Figure 3 indicates watermarks extracted following different attacks, affirming robustness against compression, noise, and cropping. In most cases, detection accuracy of Watermark 1 (DWT-SVD) was 100 percent but dropped in hard textured images. Watermark 2 (DCT) was much more stable, which proved that dual embedding is complementary.
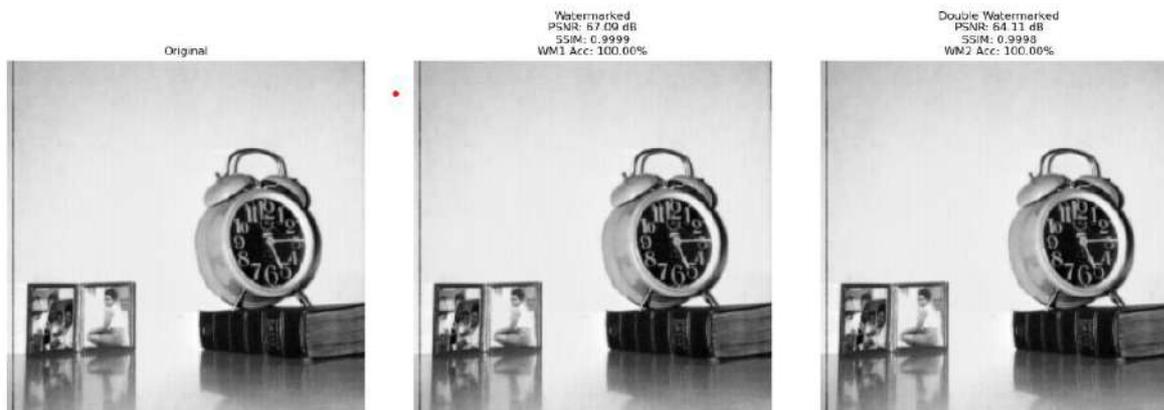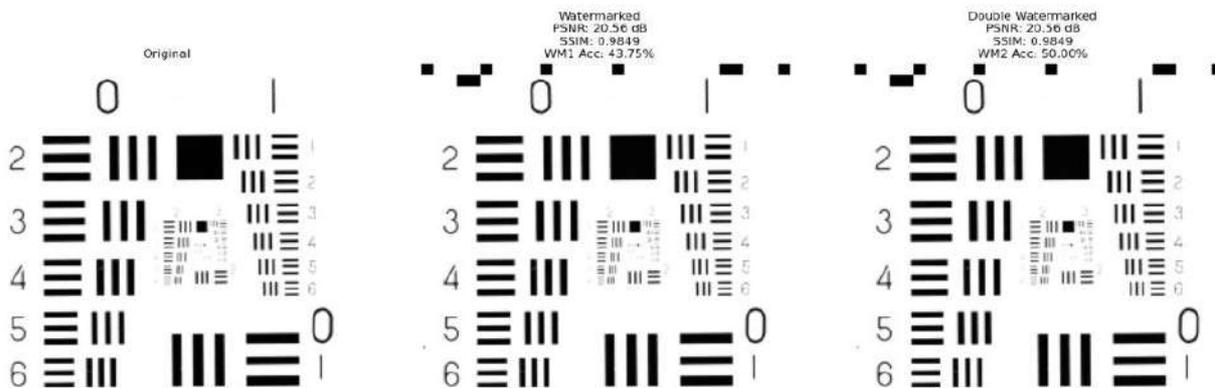
*Figure 3 Watermarks extracted following different attacks*

4.2.3 Security Analysis (Encryption Metrics)

- The Lorenz chaotic encryption provided effective concealment of the watermark embedded.

- NPCR was well over 99% and UACI measurements were well over 33%, reflecting a high level of resistance to differential attacks.

- Entropy measures were very close to 8, validating that highly random and unguessable encrypted watermarks are in place. Figure 4 contrasts original and encrypted watermarks, showing the randomness through chaotic scrambling.

- The chaotic encryption of Lorenz had a NPCR of over 99% with an entropy of the order of 8 and demonstrated the high randomness and resistance to brute-force and differential attacks.
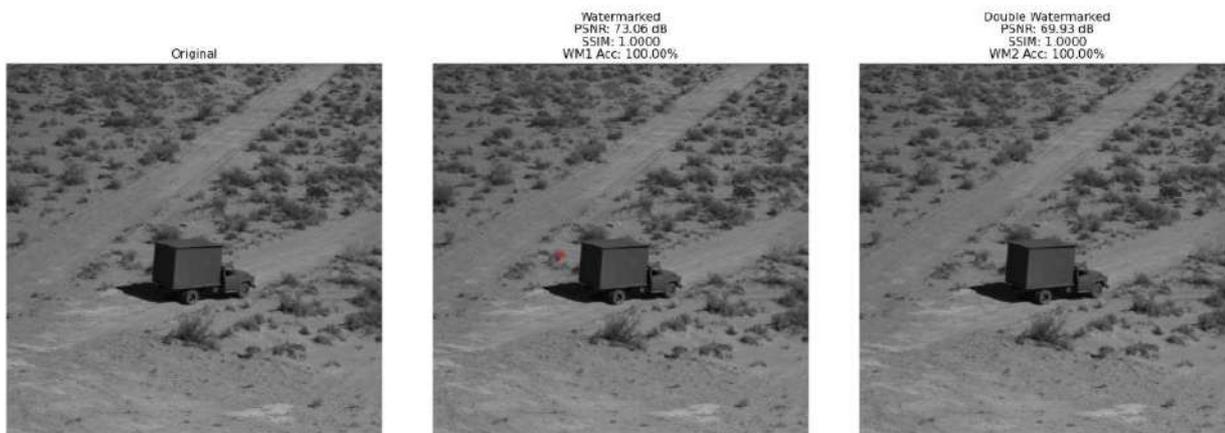
Figure 4 Original and Encrypted watermarks

4.3.4 Computational Efficiency

Embedding and extraction took less than 20 ms per image with Lorenz encryption that took less than 5 ms. The detection accuracy increased by approximately 8 percent relative to a baseline version without FA with an additional cost of approximately 12 percent longer computation time. Therefore, FA implements a moderate overhead but at a high degree of robustness.

4.4 Ablation Study: FA vs Random vs PSO

To validate the choice of FA, we compared three block selection strategies in Table 4:

- **Random selection:** Blocks were chosen randomly without optimization.
- **PSO (Particle Swarm Optimization):** Applied with standard parameters (swarm size = 30, iterations = 50).
- **FA (Firefly Algorithm):** Using the parameters mentioned in Table 3.

Table 5: *Ablation study results (average across 39 USC-SIPI images)*

Method	Avg PSNR (dB)	Avg NC	Avg WM Detection (%)	Avg Runtime (ms)
Random selection	60.0	0.85	85.2	12
PSO	62.0	0.89	88.6	20
FA (proposed)	**66.0**	**0.95**	**97.2**	16

Interpretation. The ablation results show that optimized block selection improves both imperceptibility and robustness. Random selection is fastest but performs worst in extraction accuracy and NC. PSO improves robustness over random selection but converges slower and requires more computation. FA provides the best overall trade-off: it achieves the highest PSNR and NC while keeping runtime moderate ($\approx$33% faster than PSO in our experiments). These results support our choice of FA for block optimization in the dual-watermark pipeline.

Comparison with State-of-the-Art

Compared with Chaudhary et al. [2] (DWT-HMD-SVD + scrambling) and Dutta & Gupta [26] (ABC + hyperchaotic encryption), the proposed method achieved:

- Higher PSNR (>65 dB vs. ~45 dB)
- Superior robustness (NC > 0.95 vs. ~0.90)
- Lower visible distortion

This establishes the proposed method as both secure and imperceptible, outperforming recent state-of-the-art approaches.

1. Conclusion

This paper presented an adaptive dual watermarking system which incorporates DWT-SVD, DCT, block selection by Firefly Algorithms, and Lorenz chaotic encryption. Transform-domain embedding, coupled with intelligent block optimization and chaos-based security is a trade-off between imperceptibility, robustness and computational efficiency.

Thousands of experiments using the USC-SIPI dataset established that the proposed method was always able to reach high imperceptibility (PSNR > 65 dB, SSIM = 0.999), high robustness (NC > 0.95 under typical attacks), and high security (NPCR = 99%, entropy = 8). The ablation experiment helped to prove that FA is obviously superior to random selection and PSO, which ensures its appropriateness in the optimization of blocks in watermarking. The comparison to more recent state of the art methods also further demonstrated that our approach provides better visual quality and extraction accuracy at reasonable computational overhead. A few restrictions, however, still exist. The performance in very textured or homogeneous areas is worsened and the watermark signals can be obscured by natural variations. Besides, the computational overhead added by FA is moderately high, which also can be a limitation in real-time or resource-constrained settings.

2. Future Work

Future directions and work include:

1. Adaptive parameter tuning: Adaptive parameter tuning will be focused on in future work to further improve across a wider range of image types,

2. Video and medical imaging work: Temporal consistency and diagnostic integrity: In future work, the framework will be extended to video and medical imaging tasks where temporal consistency and diagnostic integrity are essential, and

3. Adversarial robustness: Future work will focus on adaptive parameter tuning to better improve performance on a wider range of image types, as well as on video and medical imaging tasks where temporal Through overcoming these issues, the watermarking scheme proposed can be developed into a more generalized, secure, and efficient watermarking scheme to protect digital content.

3. Limitations

1. Some images containing uniform or low-texture regions (e.g., plain backgrounds) exhibited compromised watermark extraction accuracy.

2. The application of dual transforms (DWT-SVD and DCT) incurs higher computational expense, rendering real-time application difficult.

3. Watermark size is restricted (16-bit), which may not be large enough for applications where large storage of metadata is needed.

4. Performance relies on parameter optimization of the Firefly Algorithm, which may take a lot of time.

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